THE

INTERNATIONAL

SCIENTIFIC SERIES

rare

THE INTERNATIONAL SCIENTIFIC SERIES.

VOLUME XXXI.

THE

# INTERNATIONAL SCIENTIFIC SERIES.

Each book complete in One Volume, 12mo, and bound in Cloth.

1. THE FORMS OF WATER IN CLOUDS AND RIVERS, ICE AND GLACIERS. By J. TYNDALL, LL. D., F. R. S. With 35 Illustrations. $1.50.
2. PHYSICS AND POLITICS; or, Thoughts on the Application of the Principles of "Natural Selection" and "Inheritance" to Political Society. By WALTER BAGEHOT. $1.50.
3. FOODS. By EDWARD SMITH, M. D., LL. B., F. R. S. With numerous Illustrations. $1.75.
4. MIND AND BODY: The Theories of their Relation. By ALEXANDER BAIN, LL. D. With 4 Illustrations. $1.50.
5. THE STUDY OF SOCIOLOGY. By HERBERT SPENCER. $1.50.
6. THE NEW CHEMISTRY. By Professor J. P. COOKE, Harvard University. With 31 Illustrations. $2.00.
7. THE CONSERVATION OF ENERGY. By BALFOUR STEWART, M. A., LL. D., F. R. S. With 14 Illustrations. $1.50.
8. ANIMAL LOCOMOTION; or, Walking, Swimming, and Flying. By J. B. PETTIGREW, M. D., F. R. S., etc. With 130 Illustrations. $1.75.
9. RESPONSIBILITY IN MENTAL DISEASE. By HENRY MAUDSLEY, M. D., $1.50.
10. THE SCIENCE OF LAW. By Professor SHELDON AMOS. $1.75.
11. ANIMAL MECHANISM: A Treatise on Terrestrial and Aërial Locomotion. By Professor E. J. MAREY, College of France. With 117 Illustrations. $1.75.
12. THE HISTORY OF THE CONFLICT BETWEEN RELIGION AND SCIENCE. By J. W. DRAPER, M. D., LL. D. $1.75.
13. THE DOCTRINE OF DESCENT AND DARWINISM. By Professor OSCAR SCHMIDT, Strasburg University. With 26 Illustrations. $1.50.
14. THE CHEMISTRY OF LIGHT AND PHOTOGRAPHY IN THEIR APPLICATION TO ART, SCIENCE, AND INDUSTRY. By Dr. HERMANN VOGEL, Royal Industrial Academy of Berlin. With 100 Illustrations. $2.00.
15. FUNGI: Their Nature and Uses. By M. C. COOKE, M. A., LL. D. Edited by the Rev. M. J. Berkeley, M. A., F. L. S. With 109 Illustrations. $1.50.
16. THE LIFE AND GROWTH OF LANGUAGE. By Professor WILLIAM DWIGHT WHITNEY, Yale College. $1 50.
17. MONEY AND THE MECHANISM OF EXCHANGE. By W. STANLEY JEVONS, M. A., F. R. S. $1.75.
18. THE NATURE OF LIGHT, with a General Account of Physical Optics. By Dr. EUGENE LOMMEL. With 188 Illustrations and a Table of Spectra in Colors. $2.00.

19. ANIMAL PARASITES AND MESSMATES. By Professor P. J. VAN BENEDEN, University of Louvain. With 83 Illustrations. $1.50.

20. FERMENTATION. By Professor P. SCHÜTZENBERGER. With 28 Illustrations. $1.50.

21. THE FIVE SENSES OF MAN. By Professor JULIUS BERNSTEIN, University of Halle. With 91 Illustrations. $1.75.

22. THE THEORY OF SOUND IN ITS RELATION TO MUSIC. By Professor PIETRO BLASERNA, Royal University of Rome. With numerous Illustrations. $1.50.

23 STUDIES IN SPECTRUM ANALYSIS. By J. NORMAN LOCKYER, F. R. S. With 7 Photographic Illustrations of Spectra, and 52 other Illustrations. $2.50.

24. A HISTORY OF THE GROWTH OF THE STEAM-ENGINE. By Professor R. H. THURSTON, Cornell University. With 163 Illustrations. $2.50.

25. EDUCATION AS A SCIENCE. By ALEXANDER BAIN, LL. D. $1.75.

26. STUDENTS' TEXT-BOOK OF COLOR ; or, Modern Chromatics. With Applications to Art and Industry. By Professor OGDEN N. ROOD, Columbia College. With 130 Illustrations. $2.00.

27. THE HUMAN SPECIES. By Professor A. DE QUATREFAGES, Museum of Natural History, Paris. $2.00.

28. THE CRAYFISH : An Introduction to the Study of Zoölogy. By T. H. HUXLEY, F. R. S. With 82 Illustrations. $1.75.

29. THE ATOMIC THEORY. By Professor A. WURTZ. Translated by E. Cleminshaw, F. C. S. With Illustrative Chart. $1.50.

30. ANIMAL LIFE AS AFFECTED BY THE NATURAL CONDITIONS OF EXISTENCE. By Professor KARL SEMPER, University of Würzburg. With 106 Illustrations and 2 Maps. $2.00.

31. SIGHT : An Exposition of the Principles of Monocular and Binocular Vision. By Professor JOSEPH LE CONTE, LL. D., University of California. With 132 Illustrations. $1.50.

32. GENERAL PHYSIOLOGY OF MUSCLES AND NERVES. By Professor I. ROSENTHAL, University of Erlangen. With 75 Illustrations. $1.50.

33. ILLUSIONS : A Psychological Study. By JAMES SULLY. $1.50.

34. THE SUN. By Professor C. A. YOUNG, College of New Jersey. With 83 Illustrations. $2.00.

35. VOLCANOES ; What they Are and What they Teach. By Professor JOHN W. JUDD, F. R. S., Royal School of Mines. With 96 Illustrations. $2.00.

36. SUICIDE : An Essay in Comparative Moral Statistics. By Professor HENRY MORSELLI, M. D., Royal University, Turin. With 4 Statistical Maps. $1.75.

37. THE FORMATION OF VEGETABLE MOULD, THROUGH THE ACTION OF WORMS. With Observations on their Habits. By CHARLES DARWIN, LL. D., F. R. S. With 15 Illustrations. $1.50.

38. THE CONCEPTS AND THEORIES OF MODERN PHYSICS. By J. B. STALLO. $1.75.

39. THE BRAIN AND ITS FUNCTIONS. By J. LUYS, Hospice Salpêtrière, Paris. With 6 Illustrations. $1.50.

40. MYTH AND SCIENCE. By TITO VIGNOLI. $1.50.

41. DISEASES OF MEMORY: An Essay in the Positive Psychology. By TH. RIBOT, author of "Heredity." $1.50.

42. ANTS, BEES, AND WASPS. A Record of Observations of the Habits of the Social Hymenoptera. By Sir JOHN LUBBOCK, Bart., F. R. S., etc. $2.00.

43. THE SCIENCE OF POLITICS. By Professor SHELDON AMOS. $1.75.

44. ANIMAL INTELLIGENCE. By GEORGE J. ROMANES, M. D., F. R. S. $1.75.

45. MAN BEFORE METALS. By Professor N. JOLY, Science Faculty of Toulouse. With 148 Illustrations. $1.75.

46. THE ORGANS OF SPEECH AND THEIR APPLICATION IN THE FORMATION OF ARTICULATE SOUNDS. By Professor G. H. VON MEYER, University of Zürich. With 47 Illustrations. $1.75.

47. FALLACIES: A View of Logic from the Practical Side. By ALFRED SIDGWICK, B. A., Oxon. $1.75.

48. ORIGIN OF CULTIVATED PLANTS. By ALPHONSE DE CANDOLLE. $2.00.

49. JELLY-FISH, STAR-FISH, AND SEA-URCHINS. A Research on Primitive Nervous Systems. By GEORGE J. ROMANES, M. D., F. R. S. With 63 Illustrations. $1.75.

50. THE COMMON SENSE OF THE EXACT SCIENCES. By WILLIAM KINGDON CLIFFORD. With 100 Figures. $1.50.

51. PHYSICAL EXPRESSION: Its Modes and Principles. By FRANCIS WARNER, M. D., Assistant Physician, London Hospital. With 51 Illustrations. $1.75.

52. ANTHROPOID APES. By Professor ROBERT HARTMANN University of Berlin. With 63 Illustrations. $1.75.

53. THE MAMMALIA IN THEIR RELATION TO PRIMEVAL TIMES. By Professor OSCAR SCHMIDT, University of Strasburg. With 51 Illustrations. $1.50.

54. COMPARATIVE LITERATURE. By Professor H. M. POSNETT, M. A., University College, Auckland. $1.75.

55. EARTHQUAKES AND OTHER EARTH MOVEMENTS. By Professor JOHN MILNE, Imperial College of Engineering, Tokio. With 38 Figures. $1.75.

56. MICROBES, FERMENTS, AND MOULDS. By E. L. TROUESSART. With 107 Illustrations. $1.50.

57. THE GEOGRAPHICAL AND GEOLOGICAL DISTRIBUTION OF ANIMALS. By Professor ANGELO HEILPRIN, Academy of Natural Sciences, Philadelphia. $2.00.

58. WEATHER. A Popular Exposition of the Nature of Weather Changes from Day to Day. With 96 Diagrams. By Hon. RALPH ABERCROMBY. $1.75.

59. ANIMAL MAGNETISM. By ALFRED BINET and CHARLES FÉRÉ, Assistant Physician, Hospice Salpêtrière, Paris. With 15 Figures. $1.50.

60. INTERNATIONAL LAW, with Materials for a Code of International Law. By Professor LEONE LEVI, King's College, London. $1.50.

61. THE GEOLOGICAL HISTORY OF PLANTS. With 79 Illustrations. By Sir J. WILLIAM DAWSON, LL. D., F. R. S. $1.75.

62. ANTHROPOLOGY. An Introduction to the Study of Man and Civilization. By EDWARD B. TYLOR, D. C. L., F. R. S. With 78 Illustrations. $2.00.

63. THE ORIGIN OF FLORAL STRUCTURES, THROUGH INSECT AND OTHER AGENCIES. By the Rev. GEORGE HENSLOW, M. A., etc. With 88 Illustrations. $1.75.

64. THE SENSES, INSTINCTS, AND INTELLIGENCE OF ANIMALS, WITH SPECIAL REFERENCE TO INSECTS. By Sir JOHN LUBBOCK, Bart., F. R. S., etc. With 118 Illustrations. $1.75.

65. THE PRIMITIVE FAMILY IN ITS ORIGIN AND DEVELOPMENT. By Dr. C. N. STARCKE, University of Copenhagen. $1.75.

66. PHYSIOLOGY OF BODILY EXERCISE. By F. LAGRANGE, M. D. $1.75.

67. THE COLORS OF ANIMALS: Their Meaning and Use. By EDWARD BAGNALL POULTON, F. R. S. With 36 Illustrations and 1 Colored Plate. $1.75.

68. SOCIALISM: New and Old. By Professor WILLIAM GRAHAM, M. A., Queen's College, Belfast. $1.75.

69. MAN AND THE GLACIAL PERIOD. By Professor G. FREDERICK WRIGHT, D. D., Oberlin Theological Seminary. With 108 Illustrations and 3 Maps. $1.75.

70. HANDBOOK OF GREEK AND LATIN PALÆOGRAPHY. By EDWARD MAUNDE THOMPSON, D. C. L., etc. $2.00.

71. A HISTORY OF CRUSTACEA. Recent Malacostraca. By the Rev. THOMAS R. R. STEBBING, M. A. With 51 Illustrations. $2.00.

72. RACE AND LANGUAGE. By Professor ANDRÉ LEFÈVRE, Anthropological School, Paris. $1.50.

73. MOVEMENT. By E. J. MAREY. Translated by ERIC PRITCHARD, M. A., M. B., B. Ch. (Oxon.). With 200 Illustrations. $1.75.

74. ICE-WORK, PRESENT AND PAST. By T. G. BONNEY, D. Sc., F. R. S., F. S. A., etc., Professor of Geology at University College, London. $1.50.

75. WHAT IS ELECTRICITY? By JOHN TROWBRIDGE, S. D., Rumford Professor and Lecturer on the Applications of Science to the Useful Arts, Harvard University. Illustrated. $1.50.

76. THE EVOLUTION OF THE ART OF MUSIC. By C. HUBERT H. PARRY, D. C. L., M. A., etc. $1.75.

New York: D. APPLETON & CO., 72 Fifth Avenue.

THE INTERNATIONAL SCIENTIFIC SERIES

# SIGHT

## AN EXPOSITION OF THE PRINCIPLES OF MONOCULAR AND BINOCULAR VISION



BY

JOSEPH LE CONTE, LL. D.

AUTHOR OF ELEMENTS OF GEOLOGY, RELIGION AND SCIENCE.
EVOLUTION AND ITS RELATION TO RELIGIOUS THOUGHT, ETC.;
AND PROFESSOR OF GEOLOGY AND NATURAL HISTORY
IN THE UNIVERSITY OF CALIFORNIA

WITH NUMEROUS ILLUSTRATIONS

*SECOND EDITION*
*REVISED AND ENLARGED*

NEW YORK
D. APPLETON AND COMPANY
1897

# PREFACE TO THE SECOND EDITION.

THERE are two classes of students of science to whom some clear and compendious exposition of the phenomena of vision would seem to be especially helpful—viz., ophthalmologists and psychologists. To the former its importance need not be urged, since it is obvious that physiology is the basis of pathology, and therefore of practice, in this as in every other department of medicine. To the latter its importance is not so generally recognized. But it is evident that the physiology of the senses, and especially of the sense of sight, forms the only sure basis of a rational psychology. Now, both these classes of students are rapidly increasing in this country, and the methods in both are becoming more and more scientific.

As an introduction to psychology, I know nothing equal to the study of the phenomena of vision, and especially of *binocular* vision. Here pure sense perception passes by insensible gradations into simplest judgments, and these latter into the more complex judgments. The simplest psychological phenomena are therefore found here. I am quite sure that if any

one will repeat the experiments contained in this little book, whether to verify or to refute the results, he will have acquired an amount of culture in scientific method which will both surprise and delight him.

But the subject is important not only to these special students, but in an eminent degree to every intelligent person, and must be intensely interesting once the field is fairly entered. But the field of binocular phenomena is an almost *closed world* to most, even intelligent, people—the phenomena have almost completely dropped out of consciousness. And yet on these very phenomena are based our judgments of size, distance, and shape, every day of our lives. Is it not strange that intelligent persons should go through life without analyzing their visual impressions, without even being conscious of phenomena on which are based judgments which are necessary for the safe conduct of physical life? We believe that this reproach is being removed, and it is to help its removal that this work is written.

In justification of my right to teach others on this subject, I would say that from early childhood I have amused myself by practicing binocular experiments, until I have acquired a facility in voluntary movements of the eyes and in analyzing the visual results which I am sure is quite exceptional. On this account some of the experiments, especially in Part III, may at first (but only at first) be found difficult to most persons.

In this second edition I have found little to *correct*. The changes are mainly in the form of *additions*. The

principal of these are the following: In Part I (1) a fuller explanation of the cause of *astigmatism;* (2) a clearer statement of the nature of *space perception* and of the *law of direction;* (3) a new mode of locating in space the visual representative of the *blind spot;* (4) a brief account of that curious substance, *visual purple*, and its probable function; and (5) a much fuller exposition of *color perception* and *color-blindness*, making it now a separate section.

I have made very little change in Part II.

Part III is the part in which I differ most fundamentally from some noted authorities. I have therefore gone over this part again carefully and verified every point, so that I feel more than ever confident of its substantial truth. I have also added in this part a chapter on the form of *phantom planes* under certain conditions. This chapter is an admirable illustration of some principles previously set forth. I have rewritten and greatly enlarged the chapter on the *comparative physiology of binocular vision*, and added also a final chapter on the *evolution of the eye*.

JOSEPH LE CONTE.

BERKELEY, CALIFORNIA, *January, 1897.*

## PREFACE TO THE FIRST EDITION.

In writing this treatise I have tried to make a book that would be intelligible and interesting to the thoughtful general reader, and at the same time profitable to even the most advanced specialist in this department. I find justification for the attempt in the fact that there is not, to my knowledge, any work covering the same ground in the English language. Vision has been treated either as a branch of optics or else as a branch of physiology of the nervous system. Helmholtz's great work on "Physiological Optics," of which there exist both a German and a French edition, is doubtless accessible to scientists, but this work is so technical that it is practically closed to all but the specialist. I believe, therefore, that the work which I now offer meets a real want, and fills a real gap in scientific literature.

The form in which the subject is here presented has been developed entirely independently, and as the result of a conscientious endeavor to make it clear to students under my instruction. As evidence of this, I would draw attention to the fact that, out of one hundred and thirty illustrations, only about twelve have

been taken from other writers. On those points in which I differ, not only in form but in matter, from other writers, I am willing to abide the judgment of those best qualified to decide.

I have devoted a large, perhaps some may think a too large, space to the discussion of binocular vision. I have done so, partly because I have devoted special attention to this department, partly because it is so very imperfectly presented by other writers, but chiefly because it seemed to me by far the most fascinating portion of the whole subject of vision.

As a means of scientific culture, the study of vision seems to me almost exceptional. It makes use of, and thus connects together, the sciences of Physics, Physiology, and Psychology. It makes the cultivation of the habit of observation and experiment possible to all; for the greatest variety of experiments may be made without expensive apparatus, or, indeed, apparatus of any kind. And, above all, it compels one to analyze the complex phenomena of Sense in his own person, and is thus a truly admirable preparation for the more difficult task of analysis of those still higher and more complex phenomena which are embraced in the science of Psychology.

BERKELEY, CALIFORNIA, *May 20, 1880.*

# TABLE OF CONTENTS.

INTRODUCTORY.



## PART I.

## *MONOCULAR VISION.*

### CHAPTER I.



### CHAPTER II.

CHAPTER V.



## PART III.

### *SOME ABSTRUSER POINTS, ESPECIALLY IN BINOCULAR VISION.*

CHAPTER I.



CHAPTER II.



CHAPTER III.

# SIGHT.

## INTRODUCTORY.

### *THE RELATION OF GENERAL SENSIBILITY TO SPECIAL SENSE.*

SENSORY nerve-fibers are cylindrical threads of microscopic fineness, terminating outwardly in the sensitive surfaces and sense-organs, and inwardly in the nerve-centers, especially the *brain*. Impressions on their outer extremity are transmitted along the fiber with a velocity of about one hundred feet per second, and determine changes in the nerve-centers, which in turn may determine changes in consciousness which we call sensation. The simplest and most general form of sensation is what is called general sensibility, or common sensation. This is a mere sense of contact, an indefinite response to external impression. It gives knowledge of externality—of the existence of the external world—but not of the properties of matter. The lowest animals possess this, and nothing more. But, as we go up the scale of animals, in order to give that wider and more accurate knowledge of the various properties of matter necessary for the complex relations of the higher animals, sensory nerve-fibers are differentiated into several kinds, so that each may give clear knowledge of a dif-

ferent property. Thus, for example, the first pair of cranial nerves—the olfactive—is specially organized to take cognizance of certain impressions, called smells, and nothing else. If, therefore, these nerve-fibers are irritated in any way, even mechanically, by scratching or pinching, they do not *feel* but *perceive* an *odor*. The second pair of cranial nerves—the optic—is specially organized in a truly wonderful way to respond to the ethereal vibrations called light, and nothing else. If, therefore, these nerves be mechanically irritated, we do not *feel* anything, but *see* a flash of *light*. In a similar manner, the eighth pair—the auditive nerve—is specially organized to respond to sound-vibrations, and nothing else; and therefore mechanical irritation of this nerve produces only the sensation of *sound*. Similarly, the ninth pair, or gustative nerve, is organized for the appreciation of taste only; and, therefore, a feeble electric current through this nerve produces a peculiar *taste*.

We have in these facts only an example of a very wide law, viz., the *law of differentiation*. In the lowest animals all the tissues and organs which are so widely distinct in the higher animals are represented by an unmodified *cellular structure*, performing all the functions of the animal body, but in an imperfect manner. Each cell in such an organism will feel like a nervous cell, contract like a muscular cell, respire like a lung-cell, or digest like a stomach-cell. As we go up the animal scale, this common structure is differentiated first into three main systems, viz., the *nutritive* or epithelial system, the *nerve*-system, and the *blood*-system: the first, presiding over absorption and elimination—i. e., exchange of *matter* between the exterior world and the organism; the second, over exchange of *force* between exterior and interior by impressions determin-

ing changes in consciousness, and by will determining changes in external phenomena; the third, presiding over exchanges between different parts of the organism. The first kind of exchange may be likened to foreign commerce; the second, to exchange of intelligence by telegraphic communication with foreign countries; the third, to the internal carrying trade. These three systems are very early differentiated in the embryo, since they are severally produced from the three primitive layers of the germinal disk, viz., the *endoderm*, the *ectoderm*, and the *mesoderm*.

Neglecting now all but the second or nervous system as we still go up, this is again differentiated into three subdivisions, viz., the *conscio-voluntary*, the *reflex*, and the *ganglionic*, each with its center and its afferent and efferent fibers. Neglecting, again, the two others, and selecting only the conscio-voluntary, the sensory fibers of this sub-system are again differentiated into five kinds, each to respond to a different kind of impression, and perceive a different property, viz., the five special sense-fibers for sight, hearing, smell, taste, and touch. Even these are probably again further differentiated; for the perception of different colors and different musical sounds is probably effected by means of *special* fibers of the optic and auditive nerves, and it is now believed that *heat*, *cold*, *pressure*, and *pain* are each perceived by distinct fibers of the nerves of feeling. Odors and tastes are almost infinite in number, but whether they are perceived each by special fibers, or by different affections of the same fibers, is not known. The following diagram (Fig. 1) illustrates these successive differentiations.

**Gradation among the Senses.**—1. *As to Response to Vibrations.*—Now all these higher special senses may

be regarded as the result of refinements of common sensation—each a more *refined touch.* Coarse vibrations are perceived by the nerves of common sensation as a *jarring.* When the vibrations are so rapid that

Fig. 1.

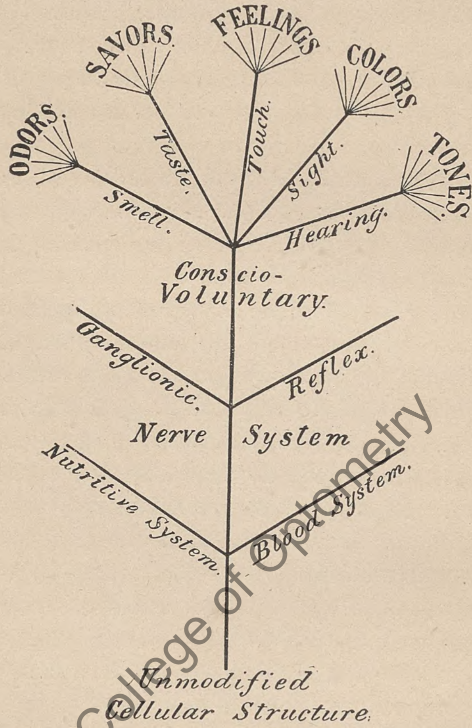



Diagram illustrating the Law of Differentiation.

there are sixteen complete movements back and forth in a second, an entirely different sensation is produced, which we call *sound.* The vibrations are no longer perceived by the nerves of common sensation, but a

special nerve—the auditive—is organized to respond to or co-vibrate with them. As the vibrations increase in number, they are perceived as higher and higher pitch, until they reach the number of about 30,000 to 40,000 in a second. This is the highest pitch the ear can perceive, the quickest vibrations the auditive nerve can respond to. Beyond this there is no sensation of any kind, but only because we have no nerve organized to co-vibrate with these more rapid undulations. These vibrations, insensible to us, may possibly be perceived by some lower animals, as, for example, insects; we can not tell. After a long interval, vibrations again appear in consciousness as light. The vibrations which produce this sensation are so rapid—the lowest about 400,000,000,000,000 in a second—that they can be conveyed only by the ethereal medium. For the perception of these vibrations, a peculiar and wonderful organization is necessary, found only in the optic nerve. Above the number just given, ethereal vibrations are perceived as different colors, in the order seen in the spectrum, until about 800,000,000,000,000 is reached.* Beyond this we have no nerve capable of responding.

2. *As to Kind of Contact.*—The gradation among the special senses may be shown in a different way. In *touch* we require direct and usually *solid* contact; in *taste*, *liquid* contact, for unless a body is soluble it can not be tasted; in *smell*, the contact is *gaseous*, for un-

* It is difficult to conceive the extreme rapidity of the vibration of a ray of light. The following illustration may help: The average or green ray vibrates about 600,000,000,000,000 times in a second. If $t$ represents the time of one vibration, then t : 1 sec. : : 1 sec. : : 20,000,000 years—i. e., the time of vibration of a ray of light is the same part of one second as one second is of twenty millions of years, or there are as many vibrations in one second as there are seconds in twenty millions of years.

less a body is volatile or vaporizable it can not be smelled. In this last case, the *perception* of objects at *a distance* begins; still it is by *direct* contact, for particles from the distant body must touch the olfactive nerve. Thus far the impression is immediate. In *hearing*, there is no direct contact of the sounding body, but the vibrations are conveyed through a medium. We perceive *at a distance*, limited only by the extent of the atmosphere and the energy of the initial vibration. This sense is therefore still *terrestrial*. In *sight*, finally, we perceive objects at a distance which is illimitable, the vibrations being conveyed by a medium which is universal, and too subtile to be recognized except as the bearer of light. This sense, therefore, is *cosmical*.

3. *As to Objectiveness.*—Again, commencing with *taste:* In this sense we distinctly perceive that the sensation is subjective—is in *us*, not in the body tasted. In *smell*, there is an equal commingling of subjectiveness and objectiveness. We distinctly *perceive* the sensation as in the nose, and yet by experience we have learned to refer it to an object at a distance. In *hearing*, we already refer the cause so completely to a distant object that there is but the smallest possible remnant of a consciousness of sensation in the ear; the sound does not seem to be in the ear, but in yonder bell. Finally, in *sight*, the impression is so completely projected outward—seems so absolutely objective—and the consciousness of anything taking place in the eye so completely lost, that it is only by careful analyses that we can be convinced of its essential subjectiveness.

*Distinction of Higher and Lower Senses.*—The order which we have given above is also the order of increasing specialization and refinement of the senses.

But only in the two higher senses—only in those senses in which there is no direct contact, but the impressing force is conveyed by means of vibration through a medium—only in these highest senses do we find that, besides the specialization of the nerve-fibers to respond to peculiar vibrations, there is also an elaborate *instrument* placed in front of the specialized nerve in order to intensify the impression and give it more definiteness. It is wholly by virtue of this supplementary instrument that we are able to hear not only sound but *music*, or to see not only light but *objects*. The lowest animals in which an optic nerve is found perceive light, but not objects; because, though the *specialized nerve* is present, the appropriate instrument is wanting. Thus hearing and sight are widely different from the other senses and stand on a higher plane. It is on these two higher senses that fine art is wholly, and science is mainly, founded. The specialized nerve and the instrument for intensifying and making definite the impression are together called the *sense-organ*. It is of the most highly specialized of these nerves and the most refined of these instruments, the highest of the sense-organs, *the eye*, that we are now about to treat.

It may be well to bear in mind and keep distinct what may be called the direct *gifts* of sight, and what are added by the mind as *judgments* based upon these gifts. The direct data are only *light*, its *intensity*, *color*, and *direction*. These are incapable of further analysis, and are therefore simple sensations. *Outline form* may possibly be added, though this may be analyzed into a combination of directions. But *solid form*, *size*, and *distance*, though they may seem to be immediately perceived, are not direct perceptions, but only very simple judgments based on the data given above. We only

state these facts now that they may be borne in mind. We hope to substantiate them hereafter.

It is well also, in order to avoid confusion, to distinguish between light *objective* and light *subjective*—light as a *vibration* of the ether and light as a *sensation*. The one belongs to physics, the other to physiology. Our main concern is with light as a sensation; but since ethereal vibration is the *cause* of the sensation, we will have much to say of this also.

### *Primary Divisions of the Subject.*

The whole subject of vision may be divided into two parts, viz., *monocular* and *binocular* vision. The former is simple vision without qualification. It includes the general phenomena characteristic of *all* vision. In addition to these there are certain other phenomena which are distinctive of the use of two eyes as *one instrument*. These constitute *binocular* vision. The distinction between these two kinds of phenomena will be fully explained in Part II.

# PART I.

## MONOCULAR VISION.

---

In this part are included only those *general* phenomena which characterize *all* vision. Besides these there are some which are distinctive of the use of the two eyes as one instrument. These belong to binocular vision.

## CHAPTER I.

### *GENERAL STRUCTURE OF THE HUMAN EYE, AND THE FORMATION OF IMAGES.*

#### SECTION I.—GENERAL STRUCTURE OF THE EYE.

**General Form and Setting.**—The eye is nearly spherical in shape, and about an inch in diameter. The socket in which it is set is not a hollow sphere, but an irregular hollow cone or pyramid. Evidently, therefore, the deeper and smaller parts of the hollow must be filled with something else. It is filled with loose connective tissue, containing fat. On this, as on a soft cushion, the eyeball rolls with ease in every direction. The eye proper is really *behind the skin* or outer integument of the face, for the skin which covers the lids turns over the edge (Fig. 2, *l l*) and passes under the lids, becoming here thin and tender mucous membrane; it is then reflected from the back part of the lid to the anterior surface of the white portion of the ball (Fig. 2, *a a*), then passes forward again over the ball as far as the clear part, or cornea (Fig. 2, *c c c*), and then entirely over this, although very closely attached. If carefully

dissected off, it would leave the eyeball behind it. This mucous covering of the anterior portion of the eyeball is called the *conjunctiva*.

**Illustrations.**—In ordinary inflammations of the eye, it is this mucous membrane which is affected, and not the eye proper. Disease of the eye proper is a far more serious matter.

When motes get into the eye they can not go beyond easy reach, viz., beyond the reflection of the mucous membrane, from the lid to the ball, at the points *a a*.

**The Muscles.**—We all know the rapidity and precision with which the eye turns in all directions. This is by means of six slender muscles. Four of these are called the *straight* muscles and two the *oblique* muscles. The *straight* muscles all rise at the bottom

FIG. 2.

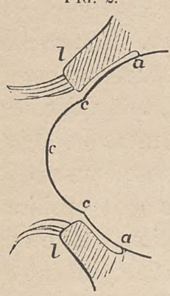
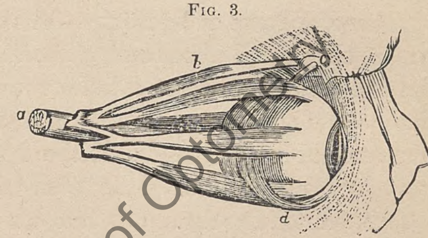



FIG. 3.




MUSCLES OF THE EYEBALL.—*a*, optic nerve; *b*, superior oblique muscle; *c*, pulley; *d*, inferior oblique. The other four are the recti.

of the conical socket, diverge as they pass forward, and grasp the eyeball above, below, on right and left side, just in front of the middle or equator of the globe (Fig. 3). They are called severally *superior*, *inferior*, *external*, and *internal rectus*. The first turns the ball upward, the second downward, the third to the right, and the fourth to the left, if we are speaking of the right

eye. This is their action expressed *generally*; but, by reference to Fig. 22, on page 51, it is seen that the axis of the eye is not coincident with the axis of the socket, and, therefore, the action of the superior rectus by itself is not only to turn the eye upward, but also to turn it inward toward the nose and rotate it on its visual axis *inward*; while the inferior rectus not only turns the eye downward, but also turns it *inward* toward the nose and rotates it on its visual axis *outward*.

The *oblique* muscles are *superior* and *inferior*. The *superior* oblique (Fig. 3, *b*) rises like the recti at the bottom of the socket, passes forward, contracts to a slender tendon, passes through a loop situated in the forward part of the socket, on the inner (nasal) and upper side (Fig. 3, *c*); it then turns upon itself backward and outward, passes over the globe obliquely across the equator, and is attached to the sclerotic, or white coat of the eye, on the outside, a little behind the equator. From its last direction it is evident that its function is to turn the eye outward and downward, and at the same time to rotate it on its visual axis *inward*—i. e., sinistrally for the right eye and dextrally for the left. The *inferior* oblique (Fig. 3, *d*) rises from the anterior, inner, and lower portion of the socket, passes outward and backward *beneath* the ball, and, crossing the equator obliquely, is attached to the ball on the outside, a little behind the equator. From its direction it is evident that its function is to turn the eye outward and upward, and at the same time to rotate it on its visual axis outward, i. e., dextrally—or like the hands of a watch—for the right and sinistrally for the left. It is seen that the oblique muscles, besides rotating the eye on its visual axis in opposite directions, co-operate with one another in turning the eye outward. This is neces-

sary to counteract the tendency of the superior and inferior recti to turn the eye inward in raising or lowering the plane of vision.

**Illustrations of these Actions.**—If we desire to look upward, we bring into action the two superior recti; if downward, the two inferior recti. In both these cases, however, the oblique muscles must co-operate. In looking upward, the inferior oblique counteracts both the inward turning and the inward rotation produced by the superior recti; in looking downward, the superior oblique counteracts both the inward turning and the *outward* rotation of the inferior recti. If we look to the right, we bring into action the exterior rectus of the right and the interior rectus of the left eye; if to the left, the external rectus of the left and internal of the right. If we desire to look at a very near object, as, for example, the root of the nose, then the two interior recti are brought into action. But we can not voluntarily bring into action the *two exterior recti* to turn the eyes outward, nor the *superior rectus* of one eye and the *inferior rectus* of the other, so as to turn the one eye upward and the other downward. The reason of this is because such motions, so far from subserving any useful purpose, would only confuse us with double images, as will be explained hereafter, and therefore have never been learned.*

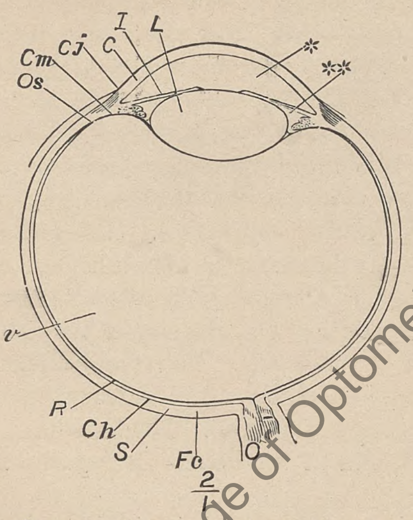
Malpositions of the eye, such as squinting, are the result of too great contraction of one of the recti muscles, usually the internal. It is often cured by cutting the muscle and allowing it to attach itself to a new point.

* Many lower animals, however, use their eyes independently of one another, and are able to turn them in different directions; and to a limited extent the same may be done by man when necessary to accomplish single vision.

**The Eyeball.**—We have thus far spoken only of what is external to the ball, viz., the socket, the muscles, etc. We come now to explain the structure of the ball itself. Suppose, then, the ball be removed from the socket, and the muscles and connective tissue be dissected away; let us examine more minutely its form and structure.

The eye thus separated is nearly a perfect globe, except that the front part is more protuberant (Fig. 4).

FIG. 4.




SECTION OF THE EYE.—*O*, optic nerve; *S*, sclerotic; *Ch*, choroid; *R*, retina; *v*, *vitreous* body; *Cm*, ciliary muscle; *Cj*, conjunctiva; *C*, cornea; *I*, iris; *L*, lens; *, aqueous humor; **, ciliary body or zonule of Zinn.

1. The outer investing coat, except the small protuberant front part, is a strong, thick, fibrous membrane of a porcelain-white color, called the *sclerotic*. This is partly exposed in the living eye, and is called the "white of the eye." By its strength, toughness, and elasticity

it gives form without rigidity. On this account the ball yields to pressure, but quickly regains its form. It also serves as the basis of attachment for the muscles. If we compare the eye to a globular watch, then the sclerotic represents the outer case.

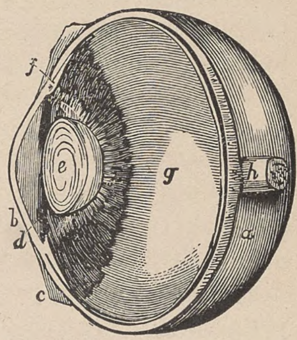
2. The more protuberant part of the ball is covered with a thick, strong, but very *transparent* membrane, called the *cornea* (*C*, Fig. 4). It corresponds to the crystal of the watch. Its function is to admit the light, and at the same time to refract it, so as to assist in forming the image, as will be explained hereafter.

3. Running across from the circle of junction of the cornea with the sclerotic, and cutting off the more protuberant clear part from the main part of the ball, and thus corresponding in position to the face of the watch, there is an opaque, colored plate called the *iris*, *I*. It is the colored part of the eye, black, brown, blue, or gray, in different individuals. This transverse plate is not perfectly flat, but protrudes a little in the middle. In its center is a round hole, called the *pupil*, corresponding in position with the hole in the watch face for attachment of the hands. The pupil seems to be jet black, because the observer looks through the pupil into the dark interior of the ball. The function of the pupil is to admit, and at the same time regulate the amount of, light.

4. *Linings.*—This much is visible to the naked eye without dissection. But if the ball be now carefully opened, the part behind the iris is found to be lined with two thin membranes. (*a.*) Immediately in contact with the sclerotic is the *choroid*, a thin, vascular membrane, the anterior layer of which is colored with black pigment, which gives it a deep-brown, velvety appearance. Its function is to quench the light as soon

as it has done its work of impressing the retina. The choroid extends forward as far as the cornea. The anterior or forward portion of the choroid, separated from the sclerotic, drawn together as a curtain, and thickened by muscular tissue, forms the *iris* already described. Just before separating from the sclerotic to form the iris, it splits into two layers: one, the anterior, goes to form the iris, as already said, while the other, the posterior, is gathered into a circular, plaited curtain, or series of converging folds, which surrounds the outer margin of the lens (to be presently described) like a dark, plaited collar. These plaits, or folds, seventy to seventy-two in number, are called the *ciliary processes* (Fig. 5, and *e*, Fig. 20, p. 38). Beneath the outer portion of this dark, plaited collar, and therefore in contact with the sclerotic, is a muscular collar, with radiating and circular fibers, called the *ciliary muscle* (Fig. 5, *f*, and Fig. 20, *d*). (*b*.) Within the choroid, innermost and most important of all, is the *retina* (Fig. 4, *R*). This is, in fact, a concave expansion of the optic nerve (*O*, Fig. 4). This nerve, coming from the brain, enters the eye-socket near its point, penetrates the sclerotic and the choroid, then spreads out within as a thin semi-transparent concave membrane of nerve-tissue, covering the whole interior of the ball as far forward as the ciliary collar. Its function is to receive and respond to the impressions of light. Its

FIG. 5.




SECTION OF EYE.—*a*, sclerotic; *b*, cornea; *c*, conjunctiva; *d*, iris; *e*, lens; *f*, ciliary muscle behind the dark ciliary processes; *g*, retina; *h*, optic nerve. (After Cleland.)

wonderful structure and functions will be explained hereafter.

5. *Contents.*—The ball thus described is not hollow and empty, but filled with refractive media, as transparent as finest glass. These are :

(*a.*) *Crystalline, or Lens.*—Immediately behind the iris, and in contact with it, is found the crystalline. It is a flattened ellipsoid, or double convex lens, as clear as finest glass, about one third of an inch in diameter and one sixth of an inch in thickness, firm enough to handle easily, but elastic and easily yielding to pressure. On section it is found to consist of layers increasing in density from surface to center, as shown in Fig. 5, *e*, and in Fig. 13, on page 31. The lens is invested with a very thin, transparent membrane, *capsule of the lens*, which not only invests it, but continues outward as a curtain, to be attached to the sclerotic near the junction of the cornea. The elastic rigidity of the sclerotic pulls gently on this curtain and makes it taut, and the taut membrane in its turn presses gently on the elastic compressible crystalline and slightly *flattens* it. We shall see the importance of this when we come to speak of the adjustment of the eye for distance.

The perfect transparency of the lens is obviously necessary for distinct vision ; cataract, a common cause of blindness, arises from its opacity.

The lens, with its continuing curtain, completely divides the interior of the ball into two compartments, an anterior and a posterior.

(*b.*) The anterior chamber is filled with a clear, watery liquor, called the *aqueous humor* (Figs. 4 and 5), a small portion of which is behind the iris, but by far the larger portion between the iris and the cornea. The two parts are in connection through the pupil. If

the cornea be punctured, the aqueous humor runs out, the clear protuberant part of the eye collapses, and the sight is for the time ruined. If, however, the wound heals without scar, or if the scar be to one side of the direct line of sight, the cornea will fill again and the sight may be recovered.

(*c*.) The posterior and much larger chamber is filled with a transparent, glassy substance, about the consistence of soft jelly, called the *vitreous humor*. This humor is in direct contact with the lens and curtain in front, and with the retina over its whole globular surface.

---

## SECTION II.—FORMATION OF THE IMAGE.

The eyeball, as thus described, may be regarded as consisting essentially of two distinct portions, viz.: 1. A nervous expansion, the retina, specialized for responding to light-vibrations; 2. An optical instrument, the lens apparatus, placed in front of the retina, and specially arranged to make the impression of light strong and definite, by *means of an image*. These two are entirely different in their origin. In embryonic development, the one is an *outgrowth* from the *brain*, the other an *ingrowth* from the epidermis and cutaneous tissues. These afterward meet and unite to form this wonderful organ.

Now the sole object of this complex instrument is the formation of a perfect *image on the retina*. Without images we would perceive light, but not objects; and distinctness of objects is exactly proportioned to distinctness of retinal images. If the image of an object is distinct, the object will be distinct; if the image

is blurred, the object, both in outline and in details of surface, will be blurred. If there is no image, no object will be visible. Therefore the image *must be* a fac-simile of the *real* object, for the *apparent* object *will be* a fac-simile of the image.

The entire distinctness of these two parts of the eye may be made plain by an illustration. Suppose, then, that the whole instrumental apparatus of lenses were removed, leaving only the concave retina. If this could be retained in a healthy condition (which of course is practically impossible), it would be easy to make a *glass instrument* which, put into the concavity, would *produce sight as perfect as*, perhaps more perfect than, *the natural eye.*

**Conditions of a Perfect Image.**—A serviceable image must be sufficiently bright, and perfectly sharp and distinct in outline and surface details. Brightness only requires a sufficient amount of light. In order to be perfectly distinct, it is necessary that rays from different points in the object, even the most contiguous, should not mix on the image, but all the rays from each point on the object must be carried to its own point on the image. Now, it is impossible that both of these conditions should be fulfilled, except by some such arrangement as we find in the eye.

For see: suppose the light to enter by a hole only, like the pupil; and, further, in order that there be light enough, let the hole be somewhat large; then the light, diverging from any point, *b*, Fig. 6, *A*, of the object *a b c*, and entering the hole of diaphragm *d d*, will form a diverging pencil, and spread out over the whole circle *b′*, on the screen *s s*. Similarly, the rays from *a* will spread out and form the circle *a′*, and from *c* the circle *c′*. Thus it is seen that rays from *widely differ-*

*ent* points in the object mix with each other on the receiving screen; much more, then, would rays from *contiguous* points of the object mix. In such a case the mixing is so great that no recognizable image is formed at all. As the hole becomes smaller, the circles of dispersion, $a'$ $b'$ $c'$, become smaller in the same proportion; and, therefore, the light from different points of the object is more and more separated on the receiving

FIG. 6.

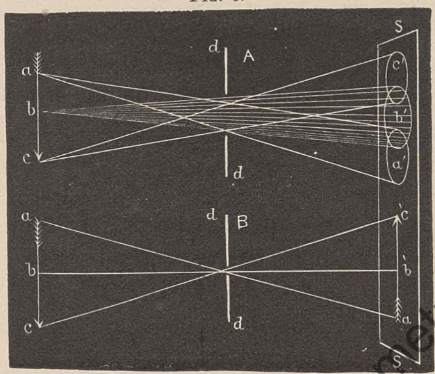



DIAGRAM SHOWING THE FORMATION OF A PINHOLE IMAGE.

screen, and the image becomes first recognizable, then more and more distinct. But, in the mean time, the *quantity* of light is becoming less and less, and therefore the image fainter and fainter. If we suppose the hole to become a mathematical point, then one ray only passes from each point to the object, and goes to its own place in the image (Fig. 6, *B*), and the conditions of distinctness are fulfilled; but the image is now infinitely faint, and therefore invisible. If, now, we try to increase the brightness by increasing the size of the hole, in proportion as we get *brightness* do we lose *distinctness*. We can not get both at the same time.

*Experiment.*—Let a room with solid shutters be darkened; let one shutter have a hole of a few inches in diameter; cover the hole with an opaque plate of sheet iron, in which there is a very small hole one tenth to one twentieth of an inch in diameter. If, now, a sheet of white paper be held a little way from the small hole, an inverted image of the external landscape will be seen on the sheet. If we increase the size of the hole, the image will be brighter, but also more blurred.

*Illustrations.*—Many simple experiments may be made illustrating this principle. A pinhole in a card will make an inverted image of a candle flame. When the sun is in eclipse, it may be examined without smoked glass, by simply allowing it to shine through a pinhole in a card upon a suitable screen. In the shade of a very thick tree-top the sun-flecks are circular like the sun; but during an eclipse they are crescentic, or even annular, according to the degree of obscuration. They are always images of the sun. Such an image may be called a *pinhole image.*

This principle is utilized in some animals. In the nautilus, e. g., the eye is a mere empty hollow lined with the retina, and opening in front by a small hole which forms a pinhole image in the retina.

**Property of a Lens.**—Now a lens has the remarkable property of accomplishing both these apparently opposite ends, viz., brightness and distinctness at the same time. If an object, *a c*, be placed before a lens, *L* (Fig. 7), of suitable shape, then *all* the rays diverging from any point, *b*, are bent so as to come together again at the point *b'*. Of the divergent pencil, *b L L*, the central ray passes straight through without deviation; rays a little way from the central are bent a little; rays farther

away are bent more and more according to their angle of divergence, so that they all meet at the same point, $b'$. Similarly all the rays proceeding from $a$, and falling on the lens, are brought to the same point, $a'$, and from $c$ to the point $c'$, and so also for every intermediate point. Thus an image is formed which is both bright and very distinct if the receiving screen is suitably

FIG. 7.

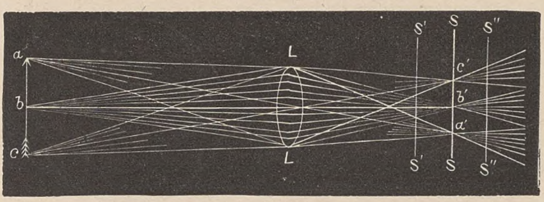



DIAGRAM SHOWING THE FORMATION OF A LENS IMAGE.

placed—i. e., at the exact place where the rays meet. The billions of rays from millions of points of the surface of the object are, as it were, sifted out by the law of refraction, and each safely conveyed to its own point in the image; so that for every *radiant* point of the object there is a corresponding *focal* point in the image. But it is evident that the screen must be suitably placed, for if it be placed too near, at $S' S'$, the rays have not yet come together; if too far, at $S'' S''$, the rays have already met, crossed, and again diverged. In both cases the image will be blurred.

Observe: 1. The image is *inverted*. It must be so, because the central rays of all the pencils cross at a certain point in the lens. This is called the *nodal point*. 2. The place of the receiving screen must be exactly at the focal point. 3. The *size* of the image will be to the size of the object as their relative distances from the nodal point. 4. As the object moves farther away, the

image comes nearer to the lens and becomes smaller. 5. It is not every lens that will make a perfect image. The lens must be of *suitable shape*.

*Application to the Eye.*—In all dioptric instruments images are formed in this way. It is in this way that images are formed in the eye. In Fig. 8 it is seen that the diverging pencils, from points *A* and *B* of the object,

FIG. 8.

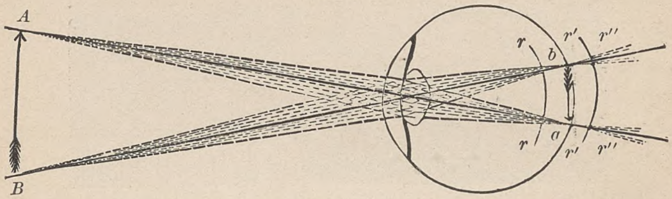



DIAGRAM ILLUSTRATING THE FORMATION OF AN IMAGE.—*A B*, the object; *a b*, the image; *r r*, retina of the normal eye.

which enter the pupil, are refracted by the lenses of the eye, and if the eye be normal, brought to a focus on the retinal screen at *a b*. Now, since the rays from every intermediate point of the object will be similarly focused, we will have a perfect image of the object painted on the retina. In the same figure $r'$ $r'$ shows the position of the retina in the myopic and $r''$ $r''$ in the hyperopic eye. Of these defects we will speak more fully hereafter.

The fundamental fact of the existence of the retinal image may be proved in many ways by observations on the dead eye: 1. If the eye of an ox be taken from the socket and the sclerotic carefully removed, so that the back parts of the eye are somewhat transparent, a miniature image of the landscape may be seen there; or, 2. If we remove the eyeball of a white rabbit, we will find that, on account of the absence of black pigment in the

choroid of these albinos, the transparency of the coats of the eye enables us to see the image, even through the sclerotic, or much more distinctly if the sclerotic be removed; or, 3. We may remove all the coats of the dead eye and replace them by a film of mica—the image will be very distinct; or, 4. The image may be seen in the living eye by means of the ophthalmoscope.

By reference to the diagram, Fig. 8, it is seen that the central rays from all radiants cross each other in the lens. This point of ray-crossing is called the *nodal point.* It is a little behind the center of the lens, and about 0·6 inch (15 mm.) in front of the retina. The size of the retinal image is as much smaller than the object as the former is nearer to the nodal point than the latter, and therefore for distant objects it must be extremely minute.

# CHAPTER II.

## *THE EYE AS AN OPTICAL INSTRUMENT.*

### SECTION I.—THE NORMAL EYE.

The further explanation of the wonderful mechanism of the eye is best brought out by a comparison with some optical instrument. We select for this purpose the photographic camera. The eye and the camera: the one a masterpiece of Nature's, the other of man's work.

We pass over, with bare mention, some obvious resemblances, in which, however, the superiority of the eye is evident: such, e. g., as the admirable arrangement of the lids for wiping and keeping bright while using, and for covering when not in use; also, the admirable arrangement of muscles, by which the eye is turned with the greatest rapidity and precision on the object to be imaged, so superior to the cumbrous movement of the camera for the same purpose. We pass over these and many other minor points to come at once to the main points of comparison.

Take, then, the eye out of the socket—the dead eye—and the camera without its sensitive plate—with only the insensitive ground-glass receiving plate. They are both now pure optical instruments, and nothing more. They are both contrived for the same purpose, viz., the formation of a perfect image on a screen properly placed.

Look into the camera from behind, and we see the inverted image on the ground-glass plate; look into the eye from behind, and we see also an inverted image on the retina. The end, therefore, is the same in the two cases. We now proceed to show that the means by which the end is attained are also similar.

1. The camera is a small, dark chamber, open to light only in front, to admit the light from the object to be imaged. It is coated inside with lampblack, so that any light from the object to be imaged or from other objects which may fall on the sides will be quenched, and not allowed to rebound by reflection, and thus fall on the image and spoil it. No light must fall on the image except that which comes directly from the object. So the eye also is a very small, dark chamber, open to light only in front, where the light must enter from the object to be imaged, and lined with dark pigment, to quench the light as soon as it has done its work of impressing its own point of the retina, and thus prevent reflection and striking some other part, and thus spoiling the image.

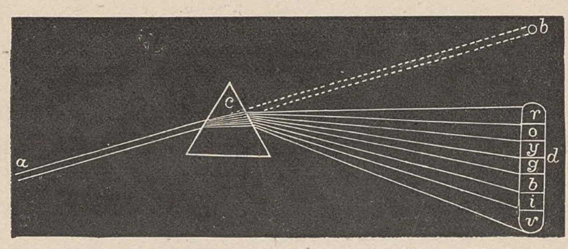
2. Both camera and eye form their images by means of a lens or a system of lenses. The manner in which these act in forming an image has already been explained (page 21). It is precisely the same in both cases. But lenses which form a perfect image are very difficult of construction. There are, especially, two main imperfections which must be corrected, viz., *chromatism* and *aberration*.

3. *Correction of Chromatism*.—In the image formed by a simple, ordinary lens, all the outlines of figures are found to be slightly edged with *rainbow hues*. If we look through such a lens at an object, the outlines of the object will be similarly edged with colors, especially

if the object lie near the margin of the field of the lens. This is explained as follows:

Ordinary sunlight, as every one knows, consists of many colors mixed together, the mixture producing the impression of *white*. If a beam of sunlight be made to pass through a glass prism, the beam is bent: but more, the different colors are *unequally* bent, so that they are separated and spread out over a considerable space. This colored space is called the spectrum. In Fig. 9 the

FIG. 9.

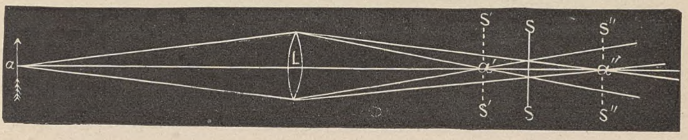



*r–v*, spectrum: *r*, red; *o*, orange; *y*, yellow; *g*, green; *b*, blue; *i*, indigo; *v*, violet.

straight beam, *a b*, is bent by the prism so as to become *a c d;* this is called *refraction.* But also the different colors are unequally bent; red is bent least and violet most, the other colors lying between these extremes; thus they are spread out over a considerable colored space. This *unequal* refraction is called *dispersion.* If we look through a prism at objects, we will find that the outlines of the objects will be edged with exactly similar colors. Now all refraction is accompanied by dispersion; therefore a simple, uncorrected lens always disperses, especially on the edges where the refraction is greatest; and, therefore, also, the images made by such a lens will be edged with color. Thus the light from the radiant *a* (Fig. 10), being white light, is dispersed; the violet rays, being more bent, reach a focus at *a′*,

but the red only at $a''$, the other colors at intermediate points. There is, therefore, no place where all the rays from the radiant come to a focus—there is no common focal point for the radiant $a$. The best place

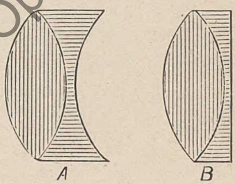
FIG. 10.




for the receiving screen would be $S\ S$, but even here there is no perfect focus. Evidently, therefore, the conditions of a perfect image are not fulfilled. This defect must be corrected. It *is* corrected in every good lens.

In order to understand how this is done, it must be remembered, first, that concave and convex lenses antagonize, and, if of equal refractive power, neutralize each other. Therefore, a combination of a double convex and a double concave lens, if of same material and of equal curvature, like Fig. 11, *A*, will produce no refraction, because the refraction produced in one direction by the convex lens is completely destroyed by refraction in the opposite direction by the concave lens. Such a combination will therefore make no image. In order that such a combination should make an image at all, it is necessary that the convexity should predominate over the concavity, as in Fig. 11, *B*. Again, it must be remembered that dispersion is not always in proportion to refraction. Some substances

FIG 11.



have a higher refractive power and a comparatively low dispersive power, and *vice versa*. This is the case with different kinds of glass.

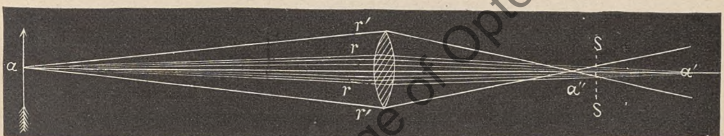
Now, suppose we select a glass with excess of refractive over dispersive power for our convex lens, and one with excess of dispersive over refractive power for our plano-concave lens (Fig. 11, *B*), and cement these together as a compound lens: it is evident that these may be so related that the plano-concave lens shall entirely correct the dispersion of the convex lens without neutralizing its refraction, and therefore the combination will be a refractive, but not a dispersive, lens, and therefore will make an image without colored edges. Such a compound lens is called *achromatic*.

This is the way in which art makes achromatic lenses, and all good optical instruments have lenses thus corrected. Now, the lenses of the eye are apparently corrected in a similar manner. The eye consists of three lenses—the aqueous, the crystalline, and the vitreous. These have curvatures of different kinds and degrees: the aqueous lens is convex in front and concave behind; the crystalline is bi-convex; the vitreous is concave in front. As its convex outer surface can not be regarded as a refracting surface, since this is in direct contact with the screen to be impressed, it may be considered as a *plano-concave* lens. The refractive powers of the material of these are also different: that of the crystalline being greatest, and the aqueous least. The dispersive powers of these have not been determined, but they probably differ in this respect also. Thus, then, we have here also a combination of different lenses, of different curvatures, and different refractive, and probably dispersive, power, and for the same purpose, viz., correction of chromatism. It is an interest-

ing historic fact that the hint for correction of chromatism by combination of lenses was taken from the structure of the eye by Euler, and afterward carried out successfully by Dollond. That the chromatism of the eye is substantially corrected is shown by the complete absence of colored edges of strongly illuminated objects, and the sharp definition of objects seen by good eyes. By close observation and refined methods, it has been recently shown that the chromatism of the eye is not perfectly corrected. It can be observed if we use only the extreme colors, red and violet.* But the degree of chromatism is so small as not to interfere at all with the accuracy of vision.

4. *Aberration.*—Another defect, much more difficult to correct, is aberration. The form of lens most easily made has a *spherical* curvature. But in such a lens there is an excess of refractive power in the *marginal* portions as compared with the *central* portions; an excess increasing with the distance from the center; therefore the focal point for marginal rays is not the

FIG. 12.




same as for the central rays, but nearer. In Fig. 12 the marginal rays, $a\,r'$, $a\,r'$, are brought to a focus at $a''$, while the central rays, $a\,r$, $a\,r$, are brought to a focus at $a'$. The best place for the receiving screen would be at $S\,S$, between these; but even there the image would not be sharp. In such a lens there is no

* Helmholtz, "Popular Lectures," p. 216.

common focal point for all the rays, and therefore the conditions of perfect image are not fulfilled—the image is blurred. This defect must be corrected. It is corrected in the best lenses.

The aberration may be greatly decreased by the use of diaphragms, which cut off all but the central rays; but in this case we get distinctness at the expense of brightness. This may be done only when the light is very intense. Again, the aberration may be reduced by using several very flat lenses, instead of one thick lens. This plan is used in many instruments. But complete correction can only be made by increasing the refraction of the central portions of the lens, and this may conceivably be accomplished in two ways, viz., either by increasing the curvature of this part or by increasing its density, and therefore its refractive index. It is by the former method that art makes the correction. By mathematical calculation, it is found that the curve must be that of an ellipse. A lens, to make a perfect image, must not be a segment of a sphere, but of the end of an ellipsoid of revolution about its major axis. It is justly considered one of the greatest triumphs of science to have calculated the curve, and of art to have carried out with success the suggestion of science.

Art has not been able to achieve success by the second method. It is impossible so to graduate the increasing density of glass from the surface to the center of a lens as to correct aberration. Now, it is apparently this second method, or perhaps both, which has been adopted by nature. The crystalline lens increases in density and refractive power from surface to center, so that it may be regarded as consisting of ideal concentric layers, increasing in density and curvature until the central nucleus is a very dense and highly refractive

spherule (Fig. 13). The surface of the cornea has the form of an ellipsoid of revolution about its major axis, and therefore doubtless contributes to the same effect. In looking at very near objects, the contraction of the pupil, also, by cutting off marginal rays, tends in the same direction. However the result may be accomplished, whether by one or by both methods, it is certain that in good eyes it is nearly if not completely achieved, for the clearness of vision is wholly conditioned on the sharpness of the retinal image.

Fig. 13.

Section showing the Structure of the Lens.

It is probable that the peculiar structure of the crystalline lens described above has also another important use in the lower animals, if not in man. Dr. Ludimar Hermann * has shown that, in a *homogeneous* lens, while the rays from radiants near the middle of the field of view, i. e., nearly directly in front, are brought to a perfect focus, the rays from radiants situated near the margins of the field of view, i. e., of very oblique pencils, are not brought to a focus. Therefore the picture formed by such a lens is distinct in the central parts, but very indistinct on the margins. Now, this defect of a homogeneous lens, Dr. Hermann shows, is entirely corrected by the peculiar structure of the crystalline; therefore this structure confers on the eye the capacity of seeing distinctly over a wide field, without changing the position of the point of sight. This capacity he calls *periscopism*. We will hereafter, however (page 79), give reasons showing that this property of the crystalline can be of little value to *man*.

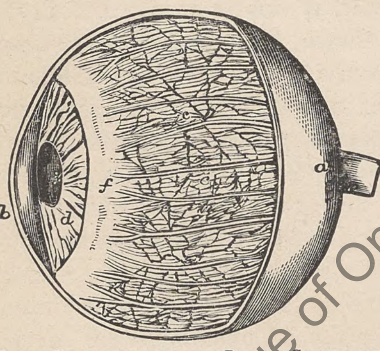
5. *Adjustment for Light.*—The delicate work done by the camera and by the eye requires a proper regulation

* "Archives des Sciences," vol. lxiii, p. 66. 1875.

of the amount of light. In both, therefore, we want some contrivance by which, when the light is very intense, a large portion may be shut out, and when the light is feeble, a larger portion may be admitted. In optical instruments this is done by means of diaphragms. In the camera we have brass caps with holes of various sizes, which may be changed and adapted to the intensity of the light. In the microscope we have a circular metallic plate, with holes of various sizes. By revolving this plate we bring a larger or a smaller hole in front of the lens.

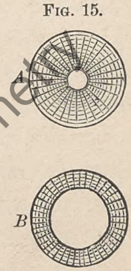
In the eye the same end is reached, in a far more perfect manner, by means of the iris. The iris (Fig.

FIG. 14.




HUMAN EYE, ENLARGED, WITH PART OF CORNEA AND SCLEROTIC REMOVED.—*a*, sclerotic; *b*, cornea; *c*, choroid; *d*, iris; *e*, pupil; *f*, ciliary muscle. (After Cleland.)

FIG. 15.




SHOWING STRUCTURE OF IRIS.

14, *d*) is an opaque circular disk, with a round hole, the pupil, in the middle. The circumference of the disk is immovably fixed to the sclerotic at its junction with the cornea; but the margin of the circular hole, or pupil, is free to move. The disk itself is composed of two sets of contractile fibers, viz., the radiating and the

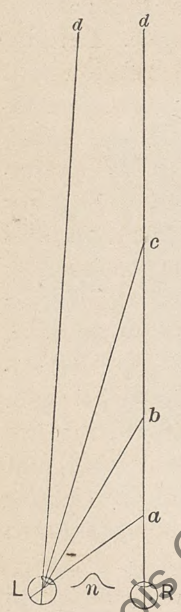
circular (Fig. 15). The radiating fibers converge from the outer margin of the iris as a fixed point, and take hold on the movable margin of the pupil, and, when they contract, pull open the pupil on every side, and thus enlarge it (Fig. 15, *B*). The circular fibers are concentric with the pupil, and are especially numerous and strong near the margin, forming there a band about one-twentieth of an inch wide. When they contract, they draw up the pupil, like a string about the mouth of a bag, and make it small (Fig. 15, *A*). We may regard the radiating fibers as *elastic*, and as contracting *passively* by elasticity when stretched; and the circular fibers as contracting *actively* under stimulus, like a muscle. Further, the circular fibers are in such sympathetic relation with the retina, that a stimulus of any kind, but especially its appropriate stimulus, light, applied to the latter, causes the former to contract, the extent of the contraction being of course in proportion to the intensity of the light. If, therefore, strong sunlight impresses the retina, the circular fibers immediately contract, the pupil becomes small, and a large portion of the light is shut out. When the light diminishes, as in twilight, the circular fibers relax, the previously stretched radiating fibers contract by elasticity, and enlarge the pupil. At night the pupil enlarges still more, in order to let in as much light as possible. Finally, if a solution of belladonna (which completely paralyzes the circular fibers) be dropped into the eye, the pupil enlarges so that the iris is reduced to a narrow dark ring.

Art, taking the hint from Nature, and striving to be not outdone, has recently constructed for the microscope a diaphragm somewhat on this plan, and therefore called iris diaphragm. It is composed of many very thin metallic plates, partly covering each other, so

arranged as to leave a polygonal or nearly circular hole in the middle, and sliding over each other in such wise that by turning a milled head in one direction they all move toward the central point and diminish the opening, while by turning in the contrary direction they all move away from the center and make the hole larger. This is confessedly a beautiful contrivance, but how inferior to the admirable work of Nature!

But contraction of the pupil takes place not only under the stimulus of light, but also in looking at very near objects. The purpose of this as already stated on page 31, is, that correction of spherical aberration is thus made more perfect.

Fig. 16.




*Experiment.*—An interesting and at the same time amusing experiment illustrating this point may be made thus: Stand in a darkish room. Cover the left eye with the hand. Gaze with the right eye at a distant point, say the wall, *d*. The optic axes are now nearly parallel, *d R*, *d L*. Tell a friend to observe the pupil of the open eye. It is probably greatly enlarged. Now, without changing at all the direction of the line of sight or position of the eye, run the point of sight, from *d*, through *c*, and *b*, up to *a*, within three inches of the eye. The pupil is seen to contract to the size of a pinhole. You seem to have exercised *voluntary control* over the muscles of the iris. But not so. The contraction is purely consensual, with strong convergence of the optic axes. If the other eye were open, it would be

seen to turn strongly inward toward the nose to look at *a*.

6. *Adjustment for Distance—Focal Adjustment Accommodation.*—We have seen that a lens, properly corrected for chromatism and aberration, makes a perfect image. But the plate or screen which receives the image and makes it visible must be placed *exactly in*

FIG. 17.

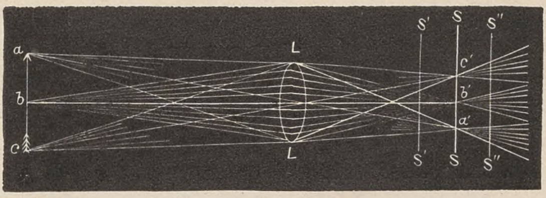



DIAGRAM SHOWING THE FORMATION OF A LENS IMAGE.

*the right place*—i. e., in the focus—otherwise the image will be blurred. We reproduce here (Fig. 17) the diagram on page 21, showing this. It is at once seen that, if the receiving plate is too near the lens—i. e., at *S′ S′*—the rays from any radiant of the object will not yet have come together at a focal point. If the receiving screen be too far from the lens, at *S″ S″*, then the rays moving in straight lines will have already met, crossed, and again spread out. It is evident that there is but one place where the image is perfect, viz., at the focal points, *S S*. Now, if this place of the image were the same for all objects at all distances, it would be only necessary to find that place, and fix the receiving plate immovably there. But the place of the image formed by any lens changes with every change in the distance of the object. As the object in front approaches, the image on the other side recedes from the lens. As the object recedes, the image approaches the lens. There-

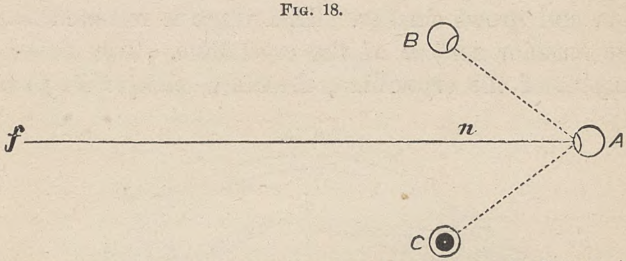
fore there must be an adjustment of the instrument for the distance of the object.

There are only two possible ways in which this adjustment can be made: Either (1), the lens remaining unchanged, the screen must advance or recede with the image, or (2), the place of the screen remaining the same, the lens must be changed so as always to throw the image on the immovable screen. The first is the mode of adjustment used in the camera, the opera-glass, the field-glass, and the telescope; the second is the mode usually used in the microscope. In the camera, for example, when the object comes nearer, we draw out the tube so as to carry the ground-glass plate a little farther back; when the object recedes, we slide up the tube so as to bring the receiving plate nearer the lens. So in the opera-glass we elongate the tube for near objects and shorten it for more distant. In the microscope, on the contrary, the image is usually thrown to the same place in the upper part of the tube. If, therefore, the object approaches nearer the lens (as it does in higher magnification), we change the lens so as to throw the image to the same place.

How is this managed in the eye? It was long believed that the adjustment was on the plan of the camera. Now, however, it is known that it is rather on the plan of the microscope. It was formerly thought that, in looking at a near object, the straight muscles, acting all together, squeezed the eye about the equatorial belt, and increased its axial diameter—in other words, made it egg-shaped—and thus carried the retinal screen farther back from the lens. But now it is known that the retinal screen remains immovable, and the lens changes its form so as to throw the image to the same place.

*Experiment.*—This is proved in the following manner: A person is chosen with good, normal young eyes. The experimenter stands in a dark room, in front of the patient, *A*, with a lighted candle in his hand, a little to one side, as in Fig. 18, *C*, while his own point

FIG. 18.



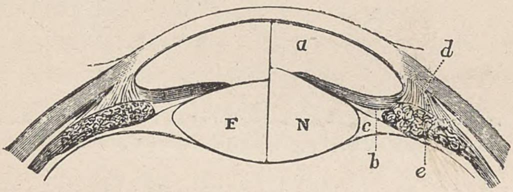

*A*, eye observed; *B*, eye of observer; *c*, section of candle-flame; *f*, a distant point of sight, and *n* a near point of sight. (After Helmholtz.)

of observation is on the other side, *B*. If the observer now looks carefully, he will see in the eye of the patient three images of the candle-flame: first, one reflected from the surface of the cornea, which is by far the brightest (Fig. 19, *a*); second, one from the anterior surface of the crystalline, much fainter (Fig. 19, *b*); third, one from the posterior surface of the crystalline, the faintest of all, and very small (*c*). Of course there is a fourth image, viz., that on the retina and which determines sight. The three images here spoken of are by reflection and have nothing to do with sight. The retinal image is by refraction, and we are not here concerned with it. Further, it will be observed that the first and second are erect images, because reflected from a convex surface, while the third is inverted, because reflected from a concave surface. Now, directing the patient to

FIG. 19.

gaze on vacancy, or a distant point, *f*, Fig. 18, we observe carefully the position and size of these several images. Then, if by request of the observer the patient transfers the point of sight to a very near point, *n*, without changing the direction, we observe that the images *a* and *c* do not change, but the image *b* changes its position and grows smaller. This image is reflected from the anterior surface of the crystalline. The *anterior surface* of the crystalline, therefore, *changes its form.*

FIG. 20.




*F*, lens adjusted to distant objects; *N*, to near objects; *a*, aqueous humor; *d*, ciliary muscle; *e*, ciliary process.

Again, the nature of the change of the image, viz., that it becomes smaller, shows that this anterior surface *becomes more convex.* By careful examination the iris, too, may be seen to *protrude* a little in the middle. Evidently, therefore, in adjusting the eye to very near objects, the crystalline becomes *thicker in the middle*, and pushes the pupil a little forward. In the accompanying diagram, Fig. 20, the crystalline lens is divided by a plane through the center. The right side, *N*, is adapted to near objects; the left, *F*, to distant objects.

*Theory of Adjustment.*—It is certain that in adjusting the eye for looking at very near objects, the lens becomes more convex. But the question, "How is this done?" is more difficult to answer. Helmholtz thinks it is done in the following manner: *

* "Optique Physiologique," p. 150.

It will be remembered that the lens is invested by a thin, transparent membrane (lens-capsule), which extends outward from its edge as a circular curtain, and is attached all around to the sclerotic, thus dividing the interior of the eye into two chambers—the anterior, filled with the aqueous, and the posterior, with the vitreous humor. It will be remembered, further, that this membrane is naturally drawn tight by the elastic rigidity of the sclerotic, and presses gently on the elastic lens, flattening it slightly. This is the normal passive condition, as when gazing at a distance. Now there are certain muscular fibers (ciliary muscle, Fig. 20, *d*) which, arising from the exterior fixed border of the iris just where it is attached to the sclerotic, run backward, radiating, and take hold upon the outer edge of the lens curtain. When these fibers contract, they pull forward the tense curtain to a smaller portion of the globe, and thus relax its tension. The relaxing of the tension of the curtain relaxes also the pressure of the capsule on the lens, which therefore immediately swells or thickens in proportion to the degree of relaxation.* According to Helmholtz, then, *we adjust the eye to near objects by contraction of the ciliary muscle.* There are other views on this subject, but this seems the most probable.

The normal eye in a *passive* state is adjusted to infinitely distant objects. By change of the form of the lens, it can adjust itself to all distances up to about five inches. The range of adjustment or of distinct vision is, therefore, within these limits. It is only at comparatively near distances, however, that the change is great. Between twenty feet and infinite distance the adjustment is almost imperceptible.

* It is probable, also, that there are certain circular fibers which, by contraction, draw together the lens curtain and thus relax the capsule. (Fuchs.)

We see, then, that the mode of adjustment of the eye is somewhat like that of the microscope—i. e., the change is in the lens, not in the position of the receiving screen. Like the microscope, but how infinitely superior! The microscope has its four-inch lens, its two-inch lens, its one-inch lens, its half-inch lens, its quarter-inch, its tenth-inch, and even its fiftieth-inch lens. It changes one for another, according to the distance of the object. But the eye changes its *one lens*, and makes it a five-inch lens, a foot lens, a twenty-foot lens, a mile lens, or a million-mile lens; for at all these distances it makes a perfect image.

---

### SECTION II.—THE ABNORMAL EYE, OR DEFECTS OF THE EYE AS AN INSTRUMENT.

In the preceding section we have attempted to bring out, in a clear and intelligible form, the beautiful structure of the eye, by comparing it with the camera and showing its superiority. But the eye of which we have been speaking is the normal or perfect eye. This normal condition is called *emmetropy*. The eye, however, is not always a perfect instrument. There are certain defects of the eye which are quite common. The principles involved in the construction of the normal eye may be still further enforced and illustrated by an explanation of these defects. Let it be observed, however, that these defects must not be regarded as the result of imperfect work on the part of Nature, but rather as the effects of misuse of the eye, accumulated by inheritance for many generations. They do not occur in animals, nor in the same degree in savage

races; and most of them are also very rare in persons living for many generations in the country.

*Emmetropy, or Normal Sight.*—The *normal or emmetropic eye* adjusts itself perfectly for all distances, from about five inches to infinity. It makes a perfect image of objects at all these distances. This is called *its range* of distinct vision. It has but one limit, viz., the nearer limit of five inches. Now in the passive state of the eye, as, for instance, in gazing on vacancy, or when the eye is taken out of the socket as a dead instrument, it is *prearranged* for perfect image of objects at an infinite distance. Its *focus of parallel rays* in a *passive state* is on the retina. For all nearer objects, a *voluntary* effort is necessary to throw the image on the retina, which effort is greater as the object is nearer, until it is limited at the distance of about five inches. The normal eye, therefore, is like a camera, which, when pushed up as much as possible, is arranged for making a perfect image of sun, or moon, or a distant landscape, but can by drawing the tube be adjusted to shorter and shorter distances up to five inches, but not nearer. This is the standard. Any considerable departure from this is a defect.

The most important defects are *myopy*, *hyperopy*, *presbyopy*, and *astigmatism*.

1. **Myopy.**—The myopic eye is not prearranged for perfect image of distant objects. Its focus for distant objects (focus of parallel rays) is not on the retina, but in front of it. The refractive power of the lenses in their passive state is too great, or else the receiving screen (retina) may be regarded as too far back from the lens, viz., at $S''$ $S''$, Fig. 7, page 21. The rays (Fig. 8, page 22, $r''$) have already reached focus, crossed, and again spread out before they reach the retina. An

object must be brought much nearer before its perfect image will be thrown on the retina. Within this farther limit of perfect image, however, it *has its own range* of adjustment, like the normal eye. The range of the normal eye is from infinite distance to five inches. In the myopic eye the range may be from a yard to four inches, or from a foot to three inches, or from six inches to two inches, or even from three inches to one inch, according to the degree of myopy. The amount of ocular adjustment or change in the lens to effect these ranges is as great as for the normal range from infinite distance to five inches, but the latter is a far more useful range. The myopic eye, therefore, is like a camera which was never intended to be used for taking distant objects, and which, therefore, when shortened to the greatest degree, is still too long in the chamber for distant objects, but is adapted only for near objects within a certain limited range.

It is evident, then, that, the defect of the myopic eye being too great refractive power of the lens in a passive state, this defect may be remedied by the use of *concave* glasses, with concavity just sufficient to correct the excess of refractive power, and therefore to throw the image of distant objects back to the retinal screen in the passive state of the eye. The eye then adjusts itself to all nearer distances, and becomes in all respects a normal eye. From the nature of the defect (structural defect), it is evident that the glasses must be worn *habitually*.

2. **Hypermetropy—Hyperopy—oversightedness.**—Hyperopy is the opposite of myopy. Like the latter, it is a structural defect, but in the opposite direction. In this case the lens is not sufficiently refractive for the length of the chamber, or the receiving screen is too

near (at $S' S'$, Fig. 7, or $r'$, Fig. 8) for the refractive power of the lens. Therefore the focus of parallel rays is behind the retina in a *passive state* of the eye. The hypermetropic eye when young usually sees well at a distance, but not very near at hand, and therefore it is apt to be confounded with slight presbyopy. The reason is, that a slight adjustment adapts the eye for perfect retinal image of distant objects; but the near limit of its range of adjustment is somewhat farther off than in the normal. When, however, the hypermetropic eye loses its power of adjustment with age, then even distant objects can not be seen distinctly. Such persons, therefore, while young, should habitually wear slightly convex glasses, which make their eyes normal. When they grow old they are compelled to have *two pairs of glasses*, one for distant objects and one for near objects; one for walking and one for reading. The hypermetropic eye may be compared to a camera which, when entirely pushed up, is too short for the imaging of any objects whatever. By drawing the tube, it may be adjusted for distant objects, but not for near objects. This defect is very common, and is peculiarly distressing. The eye *never rests*, but is always under the strain of accommodation even for distant objects.

3. **Presbyopy, or Old-sightedness.**—This defect is often called *long-sightedness*, or *farsightedness*; but this is a misnomer, based on a misconception of its true nature. It is obviously impossible to have an eye more long-sighted than the normal eye, for this defines with perfect distinctness the most distant objects, such as the moon or the sun when the dazzling effect is prevented by smoked glass. It is usually regarded as a defect the reverse of near-sightedness. As near-sightedness is the result of *too great* refractive power in a passive condi-

tion, so this is supposed to be a *too small* refractive power in the same condition. As the myopic eye throws the focus of parallel rays in front of the retina, so it is supposed the presbyopic eye throws the focus of parallel rays behind the retina, because the retina is too near the lens, at $S'$ $S'$, Fig. 7, page 21. It is further supposed that the change which takes place with age is a flattening, and therefore a loss of refractive power, of the lenses of the eye. It is constantly asserted, therefore, that the myopic eye may be expected to become normal with age.

Now this view of the nature of presbyopy is wholly wrong. The presbyopic eye sees distant objects perfectly well, and precisely like the normal eye. *Its passive structure is therefore unaltered.* It makes a perfect image of distant objects on the retina, like the normal eye. Its focus of parallel rays is *on* the retina, not behind it. It is therefore normal in its passive state, or in its structure. The defect, therefore, consists not in a change of the structure which originally adapted it to the imaging of distant objects, but in the loss of *power to adjust for near objects.* And this loss of adjusting power is, again, probably the result of loss of the elasticity of the crystalline lens. In the normal young eye, when the ciliary muscle pulls forward the lens curtain, and thus relaxes its tension, the lens by its elasticity swells and thickens, and becomes more refractive. In the presbyopic eye, the ciliary muscle pulls, and the curtain or capsule relaxes its tension, in vain; the lens, for want of elasticity, does not swell out. Therefore the remedy for presbyopy is the use of convex glasses, *not habitually*, not in looking at distant objects, but only in looking at or imaging near objects. The putting on of convex glasses does not make the

presbyopic eye normal, as the use of concave glasses makes the myopic eye, or convex glasses the hyperopic eye; therefore they cannot be worn habitually. In looking at near objects, it uses glasses; in looking at distant objects, the glasses are removed. Myopy is a *structural* defect; presbyopy is a *functional* defect. One is a defect of prearrangement of the instrument; the other is a loss of power to adjust the instrument. To compare with the camera again: the presbyopic eye is like a camera which was originally arranged for distant objects, and by drawing the tube could be adjusted for near objects also, but, through age and misuse and *rust*, the draw-tube has become so stiff that the apparatus for adjustment no longer works. It still operates well for distant objects, but can not be adjusted for nearer objects. If we desire to image a near object in such a camera, obviously we must supplement its lens with another convex lens.

From what has been said it is evident that the myopic eye does not improve with age, and finally become normal, as many suppose. Myopic persons continue to wear glasses of the same curvature until sixty or seventy years of age. I have never known a strongly myopic person who discontinued the use of glasses as he grew older. The same change, however, takes place in the myopic as in the normal eye—i. e., the *loss of adjustment.* In all young eyes there is a range of adjustment between a nearer and a farther limit; in the normal eye it is between five inches, near limit, and infinite distance, the farther limit (if limit it can be called); in the myopic eye the nearer limit may be two inches, the farther limit four inches, or it may be between three and six inches, or four inches and one foot, according to the degree of myopy. Now, with advancing age,

the nearer limit—i. e., the limit of adjustment—recedes. In the normal eye it is first eight inches, then one foot, then three feet, etc., until, when adjustment is entirely lost, it reaches the farther limit, and there is but one distance of distinct vision ; but the farther limit—i. e., structural limit, does not change. So also in the myopic eye, with advancing age, the nearer limit or limit of adjustment recedes, but not the farther limit or structural limit. This remains the same. But, as this was always too near for useful vision, glasses must still be worn. The same glasses, however, will no longer do for all distances. An old myopic speaker will lift up his glasses to read his notes. Thus it is evident that myopy and presbyopy may exist in the same individual.

In extreme old age, when the tissues begin to break down, it is probable that some flattening of the eye may take place. To such persons it would be necessary to wear weak convex glasses, even for distant objects. But this is not ordinary presbyopy. In fact, it is probable that in most of such cases there has been slight hyperopy. There is another possible explanation, however, viz., a progressive flattening of the lens by age, but corrected by *permanent* accommodation, until at last the lens becomes too flat to be accommodated even for distant objects, and therefore two glasses must be used.

4. **Astigmatism—Dim-sightedness.**—In all the other defects there is clear sight at *some* distance, although it may not be a *convenient* distance. In this there is no perfect image, and therefore no clear sight at *any* distance. In the perfect eye, and also in the cases of imperfect eye thus far explained, the form of the lenses is that of a spheroid of revolution about the visual axis—the curvature and the refraction is the same in all

directions—i. e., on all meridians. This is necessary in order to bring all the rays from any radiant to a single focal *point.* But eyes are found in which the *horizontal* curvature of the cornea or of the lens, or of both, is different from the vertical curvature—the curvature is ellipsoid, with long diameter at right angles to the optic axis. Such eyes are said to be astigmatic, because the rays from any radiant are brought, not to a *single* focal *point*, but to *two* focal *lines*, a horizontal and a vertical, which are shorter or longer, and at a less or greater distance apart, according to the degree of astigmatism. A slight astigmatism is very common, and often exists unknown to the subject.

*Test for Astigmatism.*—This defect may be detected by looking at a cross of considerable size +. If the eye is astigmatic, the vertical and horizontal lines are not equally distinct at every distance. At a certain distance the vertical, and at another the horizontal, line is most distinct.

*Explanation.*—The cause of this defect is difficult to explain in popular language. I have used the following method in my classes. Observe : 1. In a perfect lens, with curvature *equal* in all directions, the *emergent* pencil of all the rays from a single radiant is a *cone* with apex at the focus. The successive sections of this cone will be circles growing smaller until it becomes a point at the focus. Beyond this the circle again enlarges without limit. This is one extreme. 2. In a *cylindrical* lens, in which there is *no curvature at all in one direction*, the emergent beam *will be a wedge*, sections of which will be a parallelogram becoming narrower and narrower until it becomes a *focal line* as long as the cylinder if the radiant is a distant one. This is

the other extreme. 3. Now, the lens of an astigmatic eye is neither a lens of equal curvature in all directions on the one hand, nor a cylindrical lens on the other, but a mean between these extremes. Its emergent beam is a complex solid, the successive sections of which are shown in Fig. 21, *B*. As it would be difficult to represent this solid except by a model, I have taken from the whole emergent beam two planes of rays, a vertical and a horizontal. Supposing the vertical curvature the greatest (the most usual case), the vertical plane of rays *a b* will meet and cross at *f* (Fig. 21, *A*), while those of the horizontal plane *c d* will meet at some more distant point, *f'*. Now, since the rays of the vertical plane will meet and cross at *f*, while those of the horizontal plane have not yet come together, it is evident that the section of the emergent beam here will be a *horizontal line.* On the other hand, since the horizontals cross at *f'*, but the verticals have already crossed and again spread into a plane, the section here of the emergent beam will be a *vertical line.*

FIG. 21.

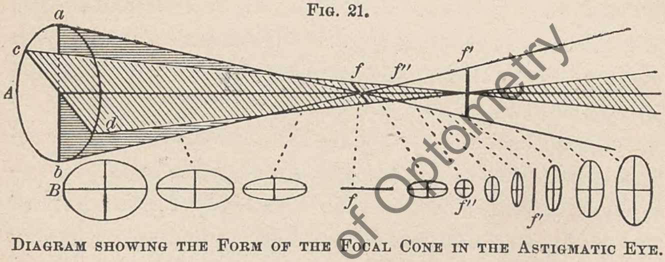



DIAGRAM SHOWING THE FORM OF THE FOCAL CONE IN THE ASTIGMATIC EYE.

For the sake of simplicity I have taken only two rectangular planes of rays. If, now, we consider all the rays, the form of the solid emergent beam is shown by the series of sections beneath (Fig. 21, *B*), and the cross

in each section is the corresponding section of the rectangular planes. It will be seen that the beam, at first circular or nearly so, flattens more and more until it becomes a horizontal plane at $f$; then it becomes more and more elliptical until its section is a small circle at $f''$; then it flattens horizontally and elongates vertically until it becomes a vertical plane at $f'$; and then finally it thickens again and at the same time enlarges indefinitely.

*Application to the Test.*—In looking at the *test cross*, the horizontal line of the cross would be seen perfectly distinctly at $f$, because there is there *no vertical blurring*, but only horizontal. This would not affect visibly the horizontal, but would render the vertical line very indistinct. At the distance $f'$, on the contrary, there is no horizontal blurring, but only vertical. The vertical line therefore would be very distinct, and the horizontal indistinct. At $f''$, the two lines are seen equally well, but neither of them quite distinctly.

*The Remedy.*—In a general way we may say that the defect is remedied by the use of more or less cylindrical lenses adapted to the kind and degree of astigmatism. To take one simplest case: Suppose the horizontal curvature is normal, but the vertical curvature too great: then the glasses must be plane horizontally and concave vertically.

## CHAPTER III.

### *EXPLANATION OF PHENOMENA OF MONOCULAR VISION.*

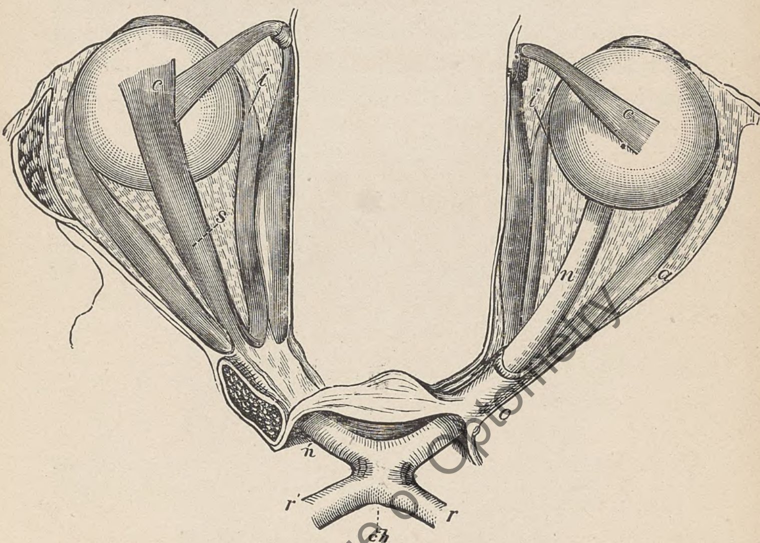
#### SECTION I.—STRUCTURE OF THE RETINA.

WE have thus far treated of the eye, and compared it with the camera, purely as an optical instrument, contrived to form an image upon a receiving screen suitably placed. We have also treated of the defects of the eye, as much as possible, from the same physical point of view as defects of an instrument. But in both the camera and the eye the image is only a means to accomplish a higher purpose, viz., to make a photographic picture in the one case and to accomplish vision in the other. We have thus far spoken as much as possible only of an *insensitive* screen, the ground-glass plate in the one case and the dead retina in the other. But in both, when accomplishing their real work, we have a *sensitive* screen, in which wonderful changes take place, viz., the iodized plate in the one and the living retina in the other. In order to understand the real function of the eye in the living animal, it is necessary that we study the structure and functions of the *retina*.

**Structure of the Retina.**—The retina, as already stated, page 15, is a thin membranous expansion of the

optic nerve. These nerves, arising from the optic lobes and the thalumus, appear first beneath the base of the brain as the optic roots, *r r′*, Fig. 22, converge, unite, and partially cross their fibers at the optic chiasm, *ch* ; then, again diverging, enter the conical eye-sockets a little to the interior of their points ; then pass through the midst of the fatty cushion behind the eye, surrounded

FIG. 22.



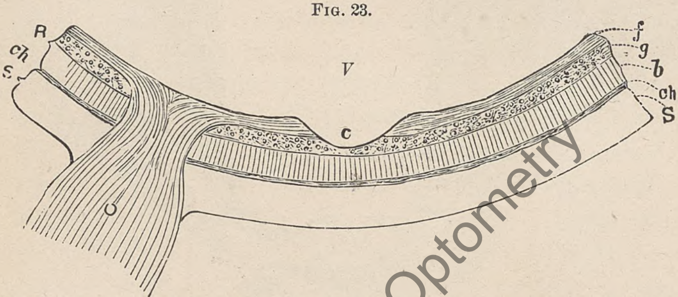

A VIEW OF THE TWO EYES, WITH OPTIC NERVES.—*ch*, optic chiasm ; *r r′*, nerve-roots ; *n* and *n′*, right and left optic nerves. (After Helmholtz.)

by the diverging recti muscles, and finally penetrate the sclerotic at a point about one eighth of an inch to the inside of the axes ; then spread out all over the interior of the ball as an innermost coat, immediately in contact with the vitreous humor, and extend as far forward as the ciliary processes, or nearly to the iris. The wide extent of this expansion and its hollow con-

cave form are necessary to give wideness to the field of view. By this means rays from objects, not only in front but far to the right and left, above and below, fall upon and impress the retina. The union of the two optic nerves at the chiasm is undoubtedly connected in some way with the wonderful co-ordinate action of the two eyes in every voluntary act of sight.

The thickness of this nervous expansion is about one hundredth of an inch, or about the thickness of thin cardboard, at the bottom of the concavity where it is thickest, but thins to one half that amount on the anterior margins; yet, under the microscope, a section

Fig. 23.

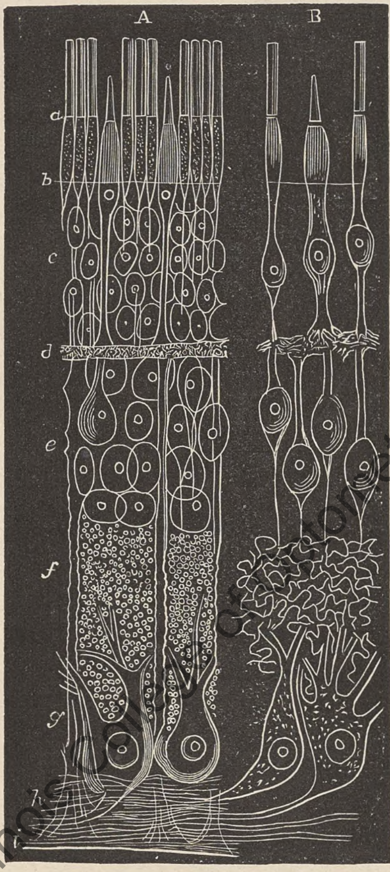



Generalized Section of Retina, etc.—*O*. optic nerve; *S*, sclerotic; *ch*, choroid; *R*, retina; *b*, bacillary layer; *g*, granular and nuclear layer; *f*, fibrous layer; *V*, vitreous humor; *c*, central spot.

through the thickness shows that it is very complex in its structure, being composed of several very distinct layers. We may first represent it on a smaller scale of enlargement as composed of three principal layers: First, the innermost layer, *f*, Fig. 23, in contact with the vitreous humor, *V*, is composed wholly of fine interlaced fibers of the optic nerve. This nerve, *o*, is seen to pierce the sclerotic and the other layers of the retina, and then to spread out as an innermost layer. This is

is called the *fibrous layer*. Second, outermost of all, and therefore in contact with the choroid, *ch*, is a remarkable layer, composed of cylindrical rods, like pen-

FIG. 24.




ENLARGED SECTION OF RETINA (after Schultze).—*A*, general view; *B*, nervous elements; *a*, bacillary layer; *b*, interior limit of this layer; *c*, external nuclear layer; *d*, external granular layer; *e*, internal nuclear layer; *f*, internal granular layer; *g*, ganglionic layer; *h*, fibrous layer, consisting of fibers of optic nerve.

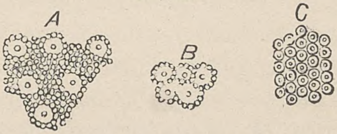
cils set on end. This is called the *bacillary* layer (*bacillum*, a small rod), or layer of rods, *b*. Third, between these is found a layer composed of granules and nucleated cells, *g*. This may be called for the present the *granular and nuclear* layer.

Further, it will be seen that these layers exist, all three, in every part of the retina except two spots. These are the spots where the optic nerve, *o*, enters, and the central spot, *c*, which is in the axis of the eye. Where the optic nerve enters, of course, no other layer can exist except the fibrous layer. In the central spot the fibrous layer is wholly wanting, and the granular and nuclear layer is almost wanting, so that the retina is here almost reduced to the bacillary layer. For this reason this spot forms a depression in the retina, and is often called the fovea or pit.

But the extreme importance of the retina requires that these layers be examined more closely. For this a much greater enlargement is necessary. Fig. 24 represents such enlargement. The fibrous layer, *h*, requires no further description; but the granular and nuclear layer is seen to be composed of two distinct layers of small granules, *d* and *f*, and two layers of large nucleated cells, *c* and *e*, and a layer of very large nucleolated cells, *g*, from which go out branching fibers. These are multipolar cells, or ganglia. It is further seen that the bacillary layer is composed of two kinds of elements, viz., slender cylindrical rods and larger but shorter conelike bodies. These are called *rods* and *cones*. It is seen, still further (Fig. 24, B), that all these different elements of the retina are in continuous connection functionally, if not physically, with each other, and with the fibers of the optic nerve. They must be regarded, therefore, as *nerve-fiber terminals*.

The bacillary layer is of the extremest interest. It consists mostly of rods, but among these are distributed the larger cones, as in Fig. 25, *A*. On the extreme anterior margin of the retina there are no cones, but only rods. On the general surface the rods are more numerous than the cones (Fig. 25, *A*). As we approach the central spot the cones become more numerous, as seen in *B*. In the *depression* of the central spot (*fovea centralis*) we find only cones, and these are of much smaller size than those in other parts of the retina, as

FIG. 25.




BACILLARY LAYER, VIEWED FROM THE OUTSIDE SURFACE.—*A*, appearance of usual surface; *B*, appearance of surface of the raised margin of central spot; *C*, surface of central spot.

seen in *C*. The rods are about $\frac{1}{350}$ inch in length and $\frac{1}{14000}$ inch in diameter. The cones are shorter and about three times thicker than the rods, except in the central depression, where they are nearly as small as the rods, being there only $\frac{1}{7000}$ to $\frac{1}{10000}$ inch in diameter. In this spot, therefore, there are probably no less than one million cones in a square $\frac{1}{10}$ inch.

**Distinctive Functions of the Layers.**—As the distinctive functions of the several sub-layers of the middle layer (granular and nuclear) are unknown, we will treat of only the three layers—inner, middle, and outer. The outer layer of rods and cones (bacillary) is undoubtedly the true *receptive* layer, which corresponds to the iodized film of the sensitized plate of the camera. These rods and cones receive and respond to the vibrations of light; they co-vibrate with the undulations of the ether.

The inner or fibrous layer *conducts* the received impression to the optic nerve; for each rod and cone is connected by a slender thread, continuous with nucleated cells of the granular layer and a fiber of the fibrous layer. The fibrous layer may, in fact, be regarded as a layer of conducting threads coming from the rods and cones, which threads are then gathered into a cord or cable, the optic nerve, which in its turn finally conducts the impression to the brain. The function of the middle layer is more obscure; but nucleated nerve-cells, and especially multipolar cells, are always generators or originators of nerve-force. They evidently have an important function. They probably act as little nerve-centers; and many unconscious, involuntary, or reflex acts of vision are probably performed by their means, without referring the sensation to the brain.

The manner in which the whole apparatus operates is briefly as follows: The light penetrates through the retina until it reaches the outer layer of rods and cones. These are specially organized to respond to or co-vibrate with the undulations of light. These vibrations are carried through the connecting threads to the fibrous layer, then through the fibers of this layer to the optic nerve, then along the fibers of the optic nerve to the gray matter of the brain, where they finally determine changes which emerge into consciousness as the sensation of light.

That we have correctly interpreted the function of the layer of rods and cones is rendered probable not only by its very remarkable and complex structure, adapting it to responsive vibrations, not only by the fact that the rods and cones are fiber terminals (all sense impressions are on terminals), but also by the peculiar properties of two spots on the retina in which all

the layers do *not* co-exist. Just where the optic nerve enters, as shown in Fig. 23, page 52, the bacillary layer is necessarily wanting, and it is the only spot in which this is the case. *Now, this spot is blind* (see page 81). Again, just in the axis of the globe, or what might be called the south pole of the eye, is the central spot or central pit. In this spot is wanting the fibrous layer and the whole of the middle layer, except some nuclear cells of the outer part (Fig. 24, *c*). The bacillary layer is here, therefore, directly exposed to the action of light. Now, this is the *most sensitive* spot of the retina. The distinctive functions of the rods and cones will come up later under color perception (page 81).

**Visual Purple.**—There has recently been found in the outer or receptive part of the rods (but not of the cones) a peculiar purple substance, which probably has some important but as yet imperfectly known function in vision, and is therefore called *visual purple.* It is bleached by light, and again restored by darkness. Photographic images (optograms) of objects may be taken on the purple retina, and by appropriate means may be fixed. These discoveries naturally excited hopes that the study of this substance would solve the mystery of sensation by reducing it to a chemical process. But these hopes have not been fulfilled; for it is now known that visual purple is not present in all animals, nor does it exist in the *cones*, and therefore is not found in the central spot of the human eye—which is nevertheless the most sensitive spot in the retina to both form and color, though not to simple faint light. It is therefore evidently not essential to the perception of either light or color.

Very recently Parinaud * has made some acute ob-

* Revue Scientifique, vol. iv, p. 134, August 3, 1895.

servations and ingenious experiments on the subject of the function of visual purple. It is wanting in night-blind animals, such as most birds and all snakes, and is abundant in nocturnal animals, such as most ruminants, all cats, and the owl among birds. According to Parinaud, its function is to produce great sensitiveness in the retina to simple faint diffused light, but not to form or color, and therefore is found in the rods but not in the cones. It is easily destroyed by light and reformed in darkness, and is therefore especially adapted to feeble light. Hence it is that in very faint light, but not in full light, by night, but not by day, we detect the *presence* of an object, though not its form—by *indirect* better than by direct vision. Direct vision is by the cones only, indirect vision by the rods mostly; and these are made very sensitive by the presence of the visual purple. This explains also the temporary night-blindness of one coming out of a brilliantly lighted room into the night. The restoration of night vision is the result of re-formation of visual purple destroyed by the brilliant light.*

---

## SECTION II.—SPACE PERCEPTION.

We have now explained both the instrument for making an image and the structure of the retina or receiving screen. We proceed to show how these co-operate to produce the phenomena of vision. There is a certain peculiarity in the general function of the retina, optic nerve, and associated brain apparatus which must first be explained and clearly apprehended, in order to understand the phenomena of vision, for it lies at their very basis.

* The decomposition of visual purple is confined to the *blue* end of the spectrum. It is not affected by *red*. Hence the relative brightness of *blue*, as compared with *red* or *yellow*, increases with the faintness of the light.

**First Law of Vision.—Law of Outward Projection of Retinal Impressions.**—An image is formed on the retinal screen. We have seen that the whole object of the complex arrangement of lenses placed in front of the retina is the formation of images. But we do not see the retinal images. We do not see anything *in the eye*, but something *outside* in space. It would seem, then, that the retinal image impresses the retina in a definite way; this impression is then conveyed by the optic nerve to the brain, and determines changes there, definite in proportion to the distinctness of the retinal image; and then the brain or the mind refers or projects this impression outward in a definite direction into space as an *external image, the sign and facsimile of an object* which produces it. We shall see hereafter how important it is that we regard what we see as *external images*, the *signs of objects* which produce them, and these external images themselves as projections outward of retinal images.

This law of outward projection is so important that we will stop a moment to show that it is not a new law specially made for the sense of sight, but only a modification of a general law of sensation. After doing so, we will proceed to illustrate by many phenomena, so as to fix it well in the mind.

**Comparison with Other Senses.**—The general law of sensation is, that irritation or stimulation in any portion of the course of a sensory fiber *is referred to its peripheral extremity*. Thus, if the sciatic nerve be laid bare in the upper thigh and then pinched, the pain is felt not at the part injured but at the termination of the nerve in the *feet and toes*. If the ulnar nerve be pinched in the hollow on the inner side of the point of the elbow, pain is felt in the *little and ring fingers*,

where this nerve is distributed. In amputated legs, as is well known, the sense of the presence of a foot remains, and often severe neuralgic pains are felt in the feet and toes. The pain, which in this case is caused by a diseased condition of the nerves at the point of amputation, is referred to the place where the diseased fibers were originally distributed. In nerves of *common sensation*, therefore, injury or disease, or stimulation of any kind in any part, is referred to the peripheral extremity of the nerve-fibers. Now the peculiarity of the optic nerve is, that it refers impressions not to its peripheral extremity only, but *beyond into space.*

But when we find great differences in the functions of tissues, such as occur in this case, we can generally find the steps which fill up the gap. A thoughtful comparison of the phenomena of the different senses will, we believe, reveal these steps. We repeat here what has already been said in a general way on page 5. Commencing with the lowest of the specialized senses, the gustative, an impression on the nerves of taste is referred, as in the case of common sensory fibers, to their peripheral extremity: the sensation is *on the tongue.* In the case of the olfactive, we have a sensation still at the peripheral extremity, i. e., *in the nose*, but also a reference to an external body at a distance as its cause. Here the objective cause and the subjective sensation are separated, and both distinct in the mind. In the case of the auditive nerve, the sensation is no longer perceived, or at least is very imperfectly perceived, in the ear, but is nearly wholly objective, i. e., referred to the distant sounding body. Finally, in the case of the optic nerve, the impression is so wholly projected outward that the very reminis-

cence of its subjectivity is entirely lost. We are perfectly unconscious of any sensation in the eye at all.

**Illustrations of this Property.**—We will now try to make this property clear by many illustrative experiments.

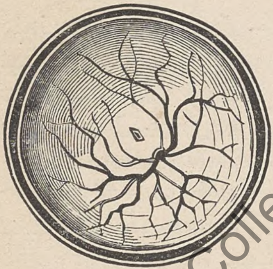
*Experiment 1.*—If the retina or the optic nerve in any portion of its course were irritated in any way, by pinching, by scratching, or by electricity, we should certainly not *feel any pain* at all, but *see* a flash of light. But where? Not at the place irritated, nor at the peripheral extremity only, not *in the eye*, but beyond *in the field of view*, and at a particular place in that field, depending on the part of the retina irritated. Of course, this experiment can not be easily made. It has been made, however, by passing a spark of electricity through the head or through the eye in such wise as to penetrate the retina or traverse the optic nerve. The phenomenon has also been observed in cases of extirpation of the eye at the moment of section of the optic nerve. (Helmholtz.)

*Experiment 2. Phosphenes.*—Press the finger into the internal corner of the eye: you perceive a brilliant colored spectrum *in the field of view* on the opposite or external side. The spectrum thus produced has a deep steel-blue center, with a brilliant yellow border, and reminds one of the beauty spots on a peacock's feather or a butterfly's wing. Remove the pressure to any other part, and the spectrum moves also, but retains its opposite position in the field of view. In this familiar experiment the pressure indents the sclerotic and causes a change or irritation on the forward portion of the retina; and any change whatever on the retina is always referred directly outward at a right angle to the point impressed, and therefore to the opposite side of the field cf view.

These colored spectra have been called phosphenes. Observe, again, the projection is in a perfectly definite direction depending on the part of the retina impressed.

*Experiment 3. Muscæ Volitantes.*—If we gaze on a white wall or ceiling, or, still better, on a bright sky, we see indistinct motes floating about in the field of view on the wall or sky, and slowly gravitating downward. Sometimes they are undulating, transparent tubes, with nucleated cells within; sometimes they are like inextricably tangled threads, or like matted masses of spider's web; sometimes they are slightly darker spots, like faint clouds. They are called *muscæ volitantes*, or flying gnats. What are they? They are specks or imperfections in the transparency of the vitreous humor. As fishes or other objects floating in midwater of a clear lake on a sunny day cast their shadows on the bottom ooze, even so these motes in the clear medium of the vitreous humor, in the strong light of the sky, cast their shadows on the *retinal bottom*. Now, as already said, all changes in the retina, of whatever kind, whether produced by images, or shadows, or mechanical irritations, are projected outward into the field of view, and appear there as something visible.

Fig. 26.



Internal View of the Retina, showing the retinal vessels ramifying over the surface, but avoiding the central spot. (After Cleland.)

*Experiment 4. Purkinje's Figures.*—Stand in a dark room with a lighted candle in hand. Shutting the left, hold the candle very near the right eye, within three or four inches, obliquely outward and forward, so that the light shall strongly illuminate the

retina. Now move the light about gently, upward, downward, back and forth, while you gaze intently on the wall opposite. Presently the field of view becomes dark from the intense impression of the light, and then, as you move the light about, there appears projected on the wall and covering its whole surface a shadowy, ghost-like image, like a branching, leafless tree, or like a great bodiless spider with many branching legs. What is it? It is an exact but enlarged image of the *blood-vessels of the retina* (Fig. 26). These come in at the entrance of the optic nerve, ramify in the middle layer, and therefore in the strong light cast their shadows on the bacillary or receptive layer, of the retina. The impression of these shadows is projected outward into the field of view, and seen there as an enlarged shadowy image. These have been called Purkinje's figures, from the discoverer.

*Experiment 5. Ocular Spectra.*—Look a moment steadily at the setting sun, and then, turning away the eye, look elsewhere—at the sky, the ground, the wall: a vivid colored spectrum of the sun (or many of them, if the eye has not been steady while regarding the sun) is projected into the field of view, and follows all the motions of the eye. This spectrum, on a bright ground, like the sky, to my eye is first green, then blue, then purple, then rose, and so gradually fades away. The spectrum is equally seen when the eye is shut; but then being projected on a dark ground, the color is apt to be complementary to that of the same spectrum seen against the bright ground of the sky. It is first blue, then yellow, then green, and so fades. The explanation is obvious. The strong impression of the image of the sun on the retina induces a change which lasts some time; the sun brands its image on the ret-

ina, but every change in the retina appears, by projection, in the field of view.

This experiment may be made in an infinite variety of ways. If at night we gaze steadily at a candle- or lamp-flame, or flame of any kind, and then turn away and look at the wall, we see a vivid colored spectrum of the flame, which gradually changes its color and fades away. In my own case, on shutting the eyes, the spectrum is first bright yellow, with deep-red border and dark olive-green corona; then it becomes greenish-yellow, and then green with red border, then red with indigo border, and so fades away. With the eyes open the changes are slightly different, and in some stages are complementary to the preceding. Again, if we look a moment through a window at a bright sky, and then quickly turn the eye to the wall, we will see a faint spectrum of the window with all its bars projected against the wall. If we look intently and steadily at any object strongly differentiated from the rest of the wall of a room, as a small picture-frame or a clock, then look to some other part of the wall, the spectrum of the object will be seen on the wall and follow the eye in its motions. This experiment succeeds best when we are just waked up in the morning, and while the retina is still sensitive from long rest.

The experiment may be varied thus: Lay a small patch of vermilion red—such as a red wafer—on a white sheet of paper, and gaze steadily at it in a strong light for a considerable time, and then turn the eye to some other part of the paper. A spectrum of the wafer will be seen, because every difference in the retina will appear as a corresponding difference in the field. It will be observed, also, that the spectrum will be bluish-green, i. e., complementary to the red of the

object. The reason seems to be that the long impression of the red produces a profounder change, or fatigue, in those rods or cones, or those portions of the cones, which co-vibrate with red; therefore, when we look elsewhere, of the different colors which make up white light, the retina is least sensitive to red, and therefore the other rays will predominate. Now these other rays, which with red make up white light, are what are called complementary to red. A mixture of these makes a bluish-green. It is difficult, however, to account for all the phenomena of the colors of spectra by this "*law of fatigue.*" The fact is, the retina is not a mere passive sensitive screen, like an iodized plate. Like all living tissue it has a self-activity of its own. Spectral images are seen on dark as well as on light fields—with the eyes shut as well as open. The retina will make images of its own, even without any external stimulus. The dark field is itself an evidence of such intrinsic activity.

Complementary spectra may be still more beautifully seen by gazing on the brilliant contrasted colors of a stained-glass window, and then turning the eyes on a white wall. The whole pattern of the window will be distinctly seen in complementary colors. We are not now, however, discussing the colors of these spectra, but only their projection into space.

Let it be observed here how differently spectral images behave from objects. When we move the eyes about, the images of objects move about on the retina, but the objects seem to remain unmoved. Spectral impressions on the retina, on the contrary, remain in the same place on the retina, and therefore their external images follow the motions of the eye.

We are now prepared to generalize from these observations. It is evident that what we call the field of

view is naught else than the *external projection into space of retinal states.* All variations of *state* of the one, whether they be images, or shadows, or brands, or mechanical irritation, whether they be normal or abnormal, are faithfully reproduced as corresponding variations of *appearances* in the other. This sense of an external visual field is ineradicable. If we shut our eyes, still the field is there, and still it represents the state of the retina. With the eyes open, we call it the *field of view*, filled with objects; with the eyes shut, it is the *field of darkness*—visible, palpable darkness, without visible objects. The one is the outward projection of the active state of the retina, crowded with its retinal images; the other is the outward projection of the comparatively passive state of the retina, without definite images. When we shut our eyes, or stand with eyes open in a perfectly dark room, the field of darkness is an actual visible field, the outlines of which we can, at least imperfectly, mark out. It is wholly different from a simple absence of visual impression. We see a dark field in front, but nothing at all behind the head. The dark field is also quite different from *blackness.* If we must describe it as of any color, we should say that it is a dark grayish or brownish field, full of irregular, confused, and ever-shifting lines and cloudings. If the retina has been previously strongly impressed, spectra are seen on this dark background when the eyes are shut. When the eyes are open, the same spectra are seen on the bright ground of the sky or wall, and the difference of the background makes the difference of the color of the spectra in the two cases. This sense of a field, although we see nothing in it, may be compared to our sense of a hand although we feel nothing with it.

Now the same inherent activity of the retina which produces the sense of a dark field with its confused markings and cloudings, will also, under certain circumstances of peculiar sensitiveness of the retina, as after complete rest in the early morning, give rise spontaneously to more definite spectra, often of beautiful colors. I have often, in bed in the morning, watched with eyes shut these splendid spectra, consisting of a colored patch surrounded with a border of complementary color, each color closing in on the center and so vanishing, while another border commences on the outside to close in in the same way. Thus, just as impressions or images made *normally* on the retina by actual objects from without are projected into the field of view and seen there as the *true* signs of objects, even so impressions made on the retina *abnormally* from *within*, by the mind or imagination, are also sometimes projected outward, and become the *delusive* signs of external objects having no existence. It is thus that the diseased brain gives rise to delusive visual phenomena.

**Second Law of Vision.—Law of Visible Direction.—Corresponding Points, Retinal and Spatial.**—We have already alluded to a particular direction of projection. We now define this direction more perfectly as a law. The direction of external projection may be exactly, or nearly exactly, defined as follows:

We have seen that the central ray of each radiant passes straight through the nodal point of the lens without deviation to the retina. Neglecting all other rays as not concerning us here, we will consider these central rays alone. Since they all pass through the nodal point, they must cross one another at that point. It is evident, then, that every point—every rod and cone—of the retina has its *invariable correspondent* in the

visual field, and *vice versa*. These two points, retinal and spatial, exchange with one another by impression and external reference along the straight lines connecting. This is represented by the diagram (Fig. 27), in which $S S$ and $R R$ represent the spatial and retinal concaves—a sort of macrocosm and microcosm — with straight lines of rays of light connecting. A ray from a point $d$ in space passes in a straight line through the nodal point $n$, and strikes a certain retinal rod $d$; that impression is projected by the rod *end on*, or nearly so—is referred back along the ray-line, or nearly so,* to the place whence it came. A mere inspection of the figure is sufficient to show that the position of all retinal images must be the

Fig. 27.

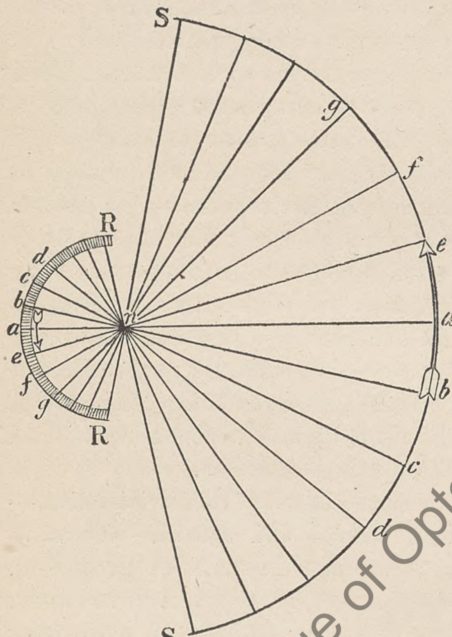



Diagram representing Corresponding Points, Retinal and Spatial.

* These two expressions, "end on" and "back along the ray-line," are not synonymous, especially for the extreme margins of the field of view. Either of them are sufficiently near the truth for my purpose. Probably the former is most exact, at least for the retinal margins.

reverse of the objects in space—that the upper part of the field of view corresponds to the lower part of the retina, and the lower part of the former to the upper part of the latter. Similarly the right and left sides of the field correspond to the left and right sides respectively of the retina.

These two laws—the law of external projection and the law of direction—are the two most fundamental laws of vision. The one shows why objects are seen externally in space; the other gives the exact place where they are seen—i. e., the relative position of objects and parts of objects. Together they explain all the phenomena of monocular vision except color. The whole science of monocular vision is but a logical explication of these two laws. It is necessary, however, to take up some points and explain them more fully by this law.

1. **Erect Vision.**—Retinal images are all inverted. External images or signs of objects are outward projections of retinal images. How, then, with inverted retinal images, do we see objects in their right position, i. e., *erect?* This question has puzzled thinkers for many centuries and many and various answers have been given.

*Theories of Erect Vision.*—1. First, there have been metaphysical theories characteristic of this class of thinkers. According to these, erect and inverted are purely relative terms. If all things are inverted, then nothing is inverted. There is no up and down to the soul, etc. 2. *Nativistic Theory.*—It is a native or inherited endowment, for which no reason can be given. 3. *Empiristic Theory.*—It is learned by experience by each individual for himself.

The first we put aside as being non-scientific. The

second and third are each true to some extent, and may and must be combined and reconciled. It is acquired by experience; yes, but not by individual experience, but by ancestral experience, acquired and accumulated through the whole line of evolution of the eye from the lowest animals to man—from the earliest times to now. To the individual, however, it is native—inherited.

But leaving aside the question of origin, a strictly scientific explanation is an analysis of the phenomena and their reduction to a general law. This law is the "law of visible direction" already explained. This law may be thus stated: *When the rays from any radiant strike the retina, the impression is referred back along the ray-line (central ray of the pencil) into space, and therefore to its proper place.* For example: The rays from a star (which is a mere radiant point) on the extreme verge of the field of view to the *right* enter the eye, pass through the nodal point, and strike the retina on its extreme anterior *left* margin; the impression is referred straight back along the ray-line, and therefore seen in its proper place on the right. A star on the left sends its rays into the eye and strikes the right side of the retina, and the impression is referred back along the ray-line to its appropriate place on the left. So also points or stars above the horizon in front impress the lower portion of the retina, and the impression is referred back along the ray-line at right angles, or nearly at right angles, to the impressed surface, and therefore upward; and radiants below the horizon, on the ground, impress the upper half of the retina and are referred downward.

**Comparison with Other Senses.**—There is nothing absolutely peculiar in this; but only a general property

of sense refined to the last degree in the case of sight, owing to the peculiar and exquisite structure of the bacillary layer of the retina. For example: Suppose, standing with our eyes bandaged, any one should with a rod push against our body. We immediately infer the direction of the external rod by the direction of the push. Suppose we were standing captive and blindfolded on the plains of Arizona surrounded by Apaches shooting arrows at us from every side. Would we not be able, by the part struck and by the direction of the push, to refer each arrow back along its line of flight to the place whence it came? Is it any wonder, then, that when the rays of light crossing one another in the nodal point punch against the interior hollow of the retina, we should infer the direction of the cause by the direction of the punch; i. e., that we should refer each radiant back to its proper place in space?

Thus it is seen that it is in nowise contrary to the general law of the senses that we should refer single radiants, like stars, back to their proper place in space and see them there. But objects are nothing else than millions of radiants, each with its own correspondent focal point in the retinal image. Each focal impression is referred back to its correspondent radiant, and thus the external image is reconstructed in space in its true position, or is reinverted in the act of projection. If we decompose objects into their component radiants it is at once seen that the question of erect vision is nothing more than a question of seeing things in their right places.*

* Some may say, some have said ("Science," vol. ii, p. 268, 1895), that we are not warranted in explaining by one law things so disparate as sensation of light and sensation of touch. The answer is plain. Direction is not a sensation, but an idea underlying all the senses. It is a matter of space perception, and therefore in this regard it is right to reduce all the senses to a common law.

After these illustrations and explanations we return to the law, and restate it thus: Every impression on the retina reaching it by a ray-line passing through the nodal point *is referred back along the same ray-line to its true place in space.* Thus, for every *radiant* point in the object there is a correspondent *focal* point in the retinal image; and every focal point is referred back along its ray-line to its own radiant, and thus the external image (object) is reinverted and reconstructed in its proper position. Or it may be otherwise expressed thus: Space in front of us is under all circumstances the outward projection of retinal states. With the eyes open, the field of *view* is the outward projection of the active or *stimulated* state of the retina; with the eyes shut, the field of *darkness* is the outward projection of the *unstimulated* or passive state of the retina. Thus the *internal retinal concave* with all its states is projected outward, and becomes the *external spatial concave*, and the two correspond, point for point. Now the lines connecting the corresponding points, external and internal, cross each other at the nodal point, and impressions reach the retina and are referred back into space along these lines; or, in other words, these corresponding points, spatial and retinal, exchange with each other by impression and external projection. This would give the true position of all objects and of all radiants, and therefore completely explains erect vision with inverted retinal image. This is easily understood by referring to Fig. 27, page 68.

We see, then, that the sense of sight is not exceptional in this property of direction reference. But what is exceptional is the marvelous perfection of this property,—the mathematical accuracy of its perception of direction. This is the result partly of the remarkable

structure of the bacillary layer. Every rod and cone has its own correspondent in space, and the extreme minuteness and therefore number of separably discernible points in space is measured by the minuteness and therefore number of the rods and cones of the bacillary layer. Also the perpendicular direction of the rods and cones to the retinal concave is probably related to the direction of projection of impressions into space, and therefore to the accuracy of the perception of direction. That this accurate perception of direction and therefore of erectness of objects is not a matter of judgment acquired by individual experience, but is inherited and therefore immediate, is proved by the fact that an infant, as soon as it takes notice at all, *turns its eyes toward the light*, and therefore must see the light in its true position. As already said, erect vision is a mere question of seeing things in their right places. A child six years old, operated on for congenital cataract and blindness, saw things in their proper position and right side up from the first, but could not judge of distance. This had to be learned by experience.*

**Illustrations of the Law of Direction.**—There are many interesting phenomena explained by this law, which thus become illustrations of the law.

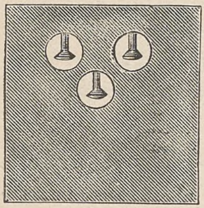
Since inverted *images* on the retina are reinverted in projection and seen erect, it is evident that *shadows* of objects thrown on the retina, not being inverted, ought to become inverted in outward projection, and therefore seen in this position in space. This is beautifully shown in the following experiment.

*Experiment 1.*—Make a pin-hole in a card, and, holding the card at four or five inches distance against the sky before the right eye with the left eye shut,

* "Revue scientifique," October 29, 1892.

bring the pin-head very near to the open eye, so that it touches the lashes, and in the line of sight: a perfect *inverted* image of the pin-head will be seen in the pin-hole. If, instead of one, we make several pin-holes, an inverted image of the pin-head will be seen *in each pin-hole*, as shown in Fig. 28. The explanation is as follows: If the pin were farther away, say six inches or more, then light from the pin would be brought to focal points and produce an *image* on the retina; and this image, being inverted, would by projection be reinverted, and the pin would be seen in its real position. In the above experiment, however, the pin is much too near the retina to form a distinct image. But nearness to the retinal screen, though unfavorable for producing an image, is most favorable for *casting a sharp shadow;* and while retinal images are inverted, retinal shadows are erect. The true image of the pin, but very much blurred, may be dimly seen on the near side of the card and covering the pin-hole. The light streaming through the pin-hole into the eye casts an erect shadow of the pin-head on the retina. This shadow is projected outward into space, and by the law of direction is inverted in the act of projection, and therefore seen in this position in the pin-hole. It is further proved to be the outward projection of a retinal shadow by the fact that, by multiplying the pin-holes or sources of light, we multiply the shadows, precisely as shadows of an object in a room are multiplied by multiplying the lights in the room.*

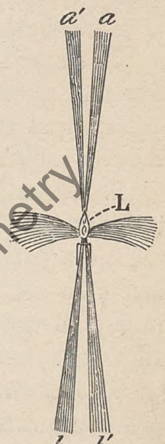
Fig. 28.



* This phenomenon was explained by the author in 1871. See "Philosophical Magazine," vol. lxi, p. 266. It had, however, been pre-

*Experiment 2.*—If we look at a strong light, such as the flame of a candle or lamp, or a gas-flame, at some distance and at night, and then bring the lids somewhat near together, we observe long rays streaming from the light in many directions, but chiefly upward and downward. Fig. 29 gives the phenomenon as I see it. The explanation is as follows: In bringing the lids near together, the moisture which suffuses the eye forms a concave lens, as in Fig. 30 (hence the phenomenon is much more conspicuous if there be considerable moisture in the eyes). This watery lens will be saddle-shaped—i. e., concave vertically and convex horizontally. Now, the rays from the light (*L*, Fig. 29) which penetrate the center of the pupil will pass directly on without refraction except what is normal, and make its image (Fig. 30, *L′*) on the central spot. But the rays which strike the curved surface of the watery lens will be bent upward to *b* and downward to *a*. Thus the light, instead of being brought to a focal point, is brought to a long focal line, *b a*, on the retina, with the image of the light in the middle at *L′*. The upper portion of this line *b L′* will be projected outward and downward, and form the downward streamers of Fig. 29; while the lower portion of the retinal impression *a L′* will be projected outward and upward, and form the upward streamers of Fig. 29. To prove this, while the streamers are conspicuous, with the finger lift up the upper lid: immediately the lower streamers

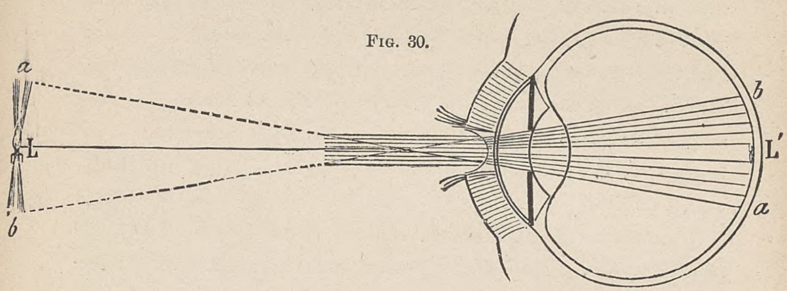
Fig. 29.




viously explained by Priestley, but forgotten. ("Nature," vol. xxiv, p. 80, 1881.)

disappear; now press down the lower lid: immediately the upper streamers disappear. Also, by shutting alter-

FIG. 30.




nately one eye and the other, it will be seen that *a b* (Fig. 29) belongs to the right eye and *a′ b′* to the left.

The much lighter diverging side-rays are more difficult to account for. I attribute them to the slight crinkling of the mucus covering the cornea in bringing the lids together.

2. **Properties of the Central Spot, and of its Representative in the Visual Field.**—We have already stated that there are two spots on the retina where the constituent layers do not all exist. The central spot is destitute of nearly all except the bacillary layer; the blind spot, of all except the fibrous layer.

The central spot (*macula centralis*) is a small depression not more than one thirtieth of an inch in diameter, situated directly in the axis of the eye, or what might be called the south pole of this globe. It differs from other parts of the retina (*a*) by wanting the fibrous and granular layers; therefore the retina is much thinner there, and the spot is consequently pit-shaped, and on this account is often called the *fovea centralis*, or central pit. Of course, the absence of other layers exposes the bacillary layer here to the direct action of

light. It differs again (*b*) by the presence of a pale-yellow coloring matter in the retinal substance; hence it is sometimes called *macula lutea*—the yellow spot. It differs, again, (*c*) in a finer organization than any other part of the retina. The bacillary layer here consists only of cones, and these are far smaller, and therefore more numerous, than elsewhere; being here, as already seen (page 55), only $\frac{1}{7000}$ to $\frac{1}{10000}$ of an inch in diameter.

**Function of the Central Spot.**—Every point on the retina, as already seen, has its correspondent or representative in the field of view. Now, what is the representative of the central spot? It is evidently the point, or rather *the line*, *of sight*, and a small space immediately about it. From its position in the axis of the eye, it is evident that on it must fall the image of the object or part of the object looked at, and of all points in the visual line or line of sight. Now, if we look steadily and attentively on any spot on the wall, and, without moving the eyes, observe the gradation of distinctness over the field, we find that the distinctness is most perfect at the point of sight and a very small area about that point, and becomes less and less as we pass outward in any direction toward the margins of the field of view. Standing two feet from the wall, I look at my pen held at arm's length against the wall, and of course see the pen distinctly. Looking still at the same spot, I move the pen to one side eight or ten inches: I now no longer see the hole in the back of the pen. I move it two feet or more to one side: I now no longer see the shape of the pen. I see an elongated object of some kind, but can not recognize it as a pen without turning my eyes and bringing its image on the central spot. Hence, to see distinctly a wide field, as

in looking at a landscape or a picture, we unconsciously and rapidly sweep the line of sight over every part, and then gather up the combined impression in the memory. To read a printed page we must run the eye from word to word, so that the image of each in succession shall fall on the central spot.

Now, the point of sight with a very small area about it corresponds to the central spot, and the margins of the field of view correspond to the extreme forward margin of the retina. Therefore the organization of the retina for distinct perception is most perfect in the central spot, and becomes gradually less and less perfect as we pass toward the anterior margin, where its perception is so imperfect that we can not tell exactly where the field of view ends, except where it is limited by some portion of the face.

Now, what is the use of this arrangement? Why would it not be much better to see equally distinctly over all portions of the field of view? I believe that the existence of the central spot is necessary to fixed, *thoughtful attention*, and this again in its turn is necessary for the development of the higher faculties of the mind. In passing down the animal scale, the central spot is quickly lost. It exists only in man and the higher monkeys. In the lower animals, it is necessary for safety that they should see well over a very wide field. In man, on the contrary, it is much more necessary that he should be able to fix undivided attention on the thing looked at. This would obviously be impossible if other things were seen with equal distinctness. This subject is more fully treated in the final chapter of this work.*

*A central spot, though differing from that of man, is found also in some birds.—"American Naturalist," vol. xxx, p. 24, 1896.

It is evident, then, that distinctness of vision is a product of two factors, viz.: first, an optical apparatus for distinct image on the retina; and, second, a retinal organization for distinct perception of the image thus formed. These two factors are perfectly independent of each other. If I hold up my pen before my eye, but very near, and then look at the sky, the outlines of the pen are blurred because the retinal image is so, but my perception is perfect. *I can observe with great accuracy the exact degree of indistinctness.* But if I hold the pen far to one side, say 90°, from the line of sight—on the extreme verge of the field of view—it is again indistinct, much more so than before, but from an entirely different cause, viz., *imperfect perception* of the retinal image. In fact, my perception is so imperfect that I can not tell whether the external image is blurred or not. Thus there are two forms of indistinctness of vision, viz., indistinctness from imperfect retinal image and indistinctness from imperfect retinal perception. The former is an effect of the optical instrument, the latter of the organization of the sensitive plate.

It is evident from the above that an elaborate structure of the lens, for making very exact images of objects on the margins of the field of view, would be of no use to man for want of corresponding distinctness of perception in the anterior margins of the retina. Therefore, as already stated on page 31, the peculiar structure of the crystalline, viz., its increasing density to the center, is of use to man only as correcting aberration, and not in conferring the faculty of periscopism. In the lower animals, however, in which periscopism is so important, this structure of the lens subserves both purposes. So far as this property is concerned, there-

fore, the structure in man may be regarded as having outlived its use.

The central spot is certainly the most sensitive and highly organized part of the retina. We can not see accurately unless the image falls on this spot. And yet it is a curious fact that other parts of the retina are more sensitive to mere light as light irrespective of form and color. In very faint light the mere presence of an object may be detected by indirect vision when it can not be detected by direct vision. It is well known that a faint star may be seen by looking a little to one side, when it can not be seen if looked at directly. The same is true of any very faint object at night.

**Minimum Visibile.**—Is there a limit to the smallness of a visible point? This question has been discussed by metaphysicians. But, as usually understood by them, there is no such thing as a *minimum visibile*. There is no point so small that it can not be seen if there be light enough. For example: a fixed star may be magnified 10 diameters, 100 diameters, 1,000 diameters, 5,000 diameters, and still it is to us a mathematical point without dimensions. How much more, therefore, is it without dimensions to the naked eye! And yet it is perfectly visible. The only sense in which science recognizes a minimum visibile is the *smallest space or object which can be seen as a surface or as a magnitude*—the smallest distance within which two points or two lines may approach each other and yet be perceived as two points or two lines. In this sense it is a legitimate inquiry; for there is here a real limit, which depends on the perfection of the eye as an instrument and the fineness of the organization of the retina.

We can best make this point clear by showing a

similar property, but far less perfect, in the lower sense of touch. There is also a *minimum tactile.*

*Experiment.*—Take a pair of dividers; stick on each point a mustard-seed shot, so that the impression on the skin shall not be too pungent. Now try, on another person whose eyes are shut, the least distance apart at which two distinct impressions can be perceived. It will be found that, on the middle of the back, it is about 3 inches; on the arm or back of the hand, it is about $\frac{1}{2}$ to $\frac{3}{4}$ inch; on the palm, about $\frac{1}{4}$ inch; on the finger-tips, about $\frac{1}{12}$ or $\frac{1}{16}$ inch; and on the tip of the tongue, about $\frac{1}{20}$ inch, or less.

Now, sight is a very refined tact, and the retina is specially organized for an extreme minimum tactile. There is no doubt that the size of the cones of the central spot determines the minimum visibile. If the images of two points fall on the same retinal cone, they will make but one impression, and therefore be seen as one; but if they are far enough apart to impress two cones, then they will be seen as two points. So also of an object: if its image on the retina be sufficient to cover two or more cones of the central spot, then it will be seen as a magnitude. Taking the diameter of central-spot cones to be $\frac{1}{7000}$ (which is the diameter given by some), the smallest distance between two points which ought to be visible at five inches distance is $\frac{1}{1000}$ of an inch. This is found to be about the fact in good eyes.

3. **Blind Spot and its Representative in the Field of View.**—This is the spot where the optic nerve enters the ball of the eye. Objects whose images fall on this spot are wholly *invisible.* It is for this reason that the point of entrance is always placed out of the axis, about $\frac{1}{6}$ inch on the nasal side. For, if it were in the axis, of course the image of the object we looked at would fall

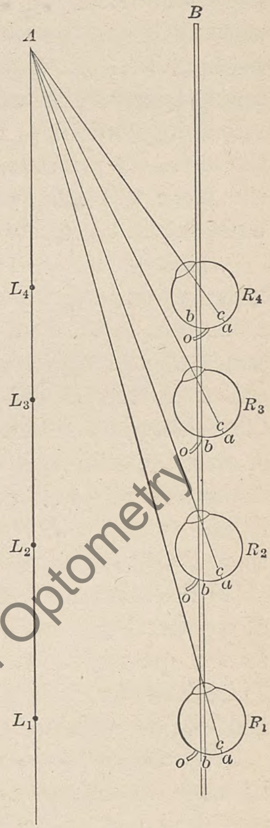
on this spot, and the object would consequently disappear from view. The structural cause of the blindness of this spot we have already explained on page 57. It is the absence of the bacillary layer; and this absence is the necessary result of the *turning back* of the fibers of the optic to terminate in the bacillary layer. As we shall see hereafter (page 308), the blind spot is peculiar to the vertebrate eye. The existence of the blind spot may be easily proved by experiments which any one can repeat.

*Experiment 1.*—Make two conspicuous marks, *A* and *B*, a few inches apart. Then shut the left eye, and


while looking steadily with the right eye at the left object, *A*, bring the paper gradually nearer and nearer: at a certain point of approach, in this case about 7 inches, *B* will disappear utterly. Continue to bring the paper nearer, still looking steadily at *A*: at a certain nearer point *B* will reappear. The explanation is as follows: At first, when the paper is at considerable distance, say 18 inches, the image of *A* is, of course, on the central spot, for the axis of the eye is directed toward this point; but the image of *B* falls a little to the internal or nasal side of the central spot, viz., between the central spot and the blind spot. Now, as the paper comes nearer, the eye turns more and more in order to regard *A*, the image of *B* travels slowly over the retina noseward until it reaches the blind spot, and the object disappears. As the paper still approaches, the image of *B* continues to travel in the same direction until it crosses over the blind spot to the other side, when the object immediately reappears.

The accompanying diagram, Fig. 31, illustrates this phenomenon. Let $A$ and $B$ represent the two objects, and $R$ and $L$ the positions of the right and left eyes respectively. The right is drawn, but the left, being shut, is not drawn, but only its position indicated by the dot. The central spot is represented by $c$, in the axis $A\ c$, and the blind spot by $o$, where the optic nerve enters. It is obvious that the image $a$ of the object $A$ will be always on $c$, and the place of the image of $B$ is on the intersection $b$ of the line $B\ b$ with the retina. Now, as the eye approaches the objects $A$ and $B$, it is seen that the image $b$ of $B$ travels toward the blind spot, $o$. At the second position of the eye, $R'$, it has not reached it. At the third position, $R''$, it is upon it. At the fourth position, $R'''$, it has already crossed over and is now on the other side. At the third position, $R''$, the object $B$ disappears from view. The distance at which the disappearance takes place will, of course, depend on the distance between the objects $A$ and $B$. If these are 3 inches apart, then the disappearance on approach from a greater distance takes place at about 1 foot, and the reappearance at about 10 inches. If

FIG. 31.



the objects be 1 foot apart, then the disappearance takes place at 48 inches, and the repearance at 38 inches.

*Experiment 2.*—Place a small piece of money on the table. Shutting the left eye, look steadily with the right at a spot on the table a little to the left of the piece, and move the piece slowly to the right while the point of sight remains fixed; or else, the piece of money remaining stationary, move the point of sight slowly to the left. At a certain distance from the point of sight the piece will disappear from view. Beyond this distance it will reappear.

*Experiment 3.*—The experiment may be varied in many ways. If, when the object *B* has disappeared from view in the first experiment, we open the left eye and shut the right, and look across the nose at the object *B*, then *A* will disappear. Thus we may make them disappear alternately. If, finally, we squint or cross the eyes in such wise that the right eye shall look at the left object *A*, and the left eye at the right object *B* (the two, *A* and *B*, had best be similar in this case), then *B* will fall on the blind spot of the right eye and *A* on the blind spot of the left eye, and they will both disappear; but a combined image of *A* and *B* on the central spots of the two eyes will be seen in the middle. This, however, is a phenomenon of binocular vision, and will be explained farther on (see page 131).

*Experiment 4.*—Any object, if not too large, may be made to disappear by causing its image to fall on the blind spot. For example: From where I now sit writing the door is distant about 10 feet. I shut my left eye and look at the door-knob. I now slowly remove the point of sight and make it travel to the left, but at the same level; when it reaches about 3 feet to the left, the door-knob disappears; when it reaches 4

feet, it reappears. Precisely in the same way a bright star or planet, like Venus or Jupiter, or even the moon, may be made to disappear completely from sight.

**Size of the Blind Spot.**—As every point in the retina has its representative in the visual field, it is evident that the size of the invisible spot is determined by the size of the blind retinal spot. We may, therefore, measure the latter by the former. I have made many experiments to determine the size of the invisible spot. At the distance of $3\frac{1}{2}$ feet (42 inches) I find the invisible spot 12 inches from the point of sight, and $3\frac{1}{2}$ inches in diameter; i. e., a circle of $3\frac{1}{2}$ inches will entirely disappear at that distance. Taking the nodal point of the lenses or the point of ray crossing at $\frac{2}{3}$ of an inch in front of the retina (it is a very little less), an invisible spot of $3\frac{1}{2}$ inches at a distance of $3\frac{1}{2}$ feet would require a blind retinal spot of a little more than $\frac{1}{20}$ inch in diameter. At 36 feet distance the invisible area would be 3 feet; it would cover a man sitting on the ground. At 100 yards distance the invisible area would cover a circle of 8 feet diameter. In a word, the angular diameter of the invisible spot is a little more than $4\frac{1}{2}°$. Helmholtz makes it a little larger than this.

**Representative in the Visual Field of the Blind Spot.**—Since every condition of the retina has its visible representative in the field of view, it may be asked, "If there be a blind spot, why do we not see it, when we look at a white wall or bright sky, as a black spot, or a dusky or dim spot, or a peculiar spot of some kind?" I answer: 1. With both eyes open there are, of course, two fields of view partly overlapping each other. Now the invisible spots in these two fields do not correspond, and therefore objects in the invisible spot of one eye

are seen perfectly by the other eye, and hence there is no invisible area for the binocular observer. But it will be objected that even with one eye we see no peculiar spot on a white wall. I therefore add: 2. That we see distinctly only a very small area about the point of sight, and distinctness decreases rapidly in going from this point in any direction. Therefore the correspondent or representative in the field of view may well be overlooked, unless it be conspicuous, i. e., strongly differentiated from the rest of the general field. 3. But if this were all, close observation would certainly detect it. The true reason is very different, and the explanation is to be sought in an entirely different direction. Writers on this subject have expected to find a visible representative, and have sought diligently but in vain for it. But the fact is, they ought not to have expected to find it. The expectation is an evidence of confusion of thought —of confounding *blackness* or *darkness* with absence of *visual* activity. Blackness or darkness is itself but the outward projection of the unimpressed state of the bacillary layer; but there is no bacillary layer here. We might as well expect to see a dark spot with our fingers as in the representative of the blind spot. A black spot, or a dark spot, or a *visible* spot of any kind, is not the representative in space of a blind or *insensitive* retinal spot. The true representative of a blind spot is simply an *invisible spot*, or, in other words, a *spot in which objects are not seen*. If we could differentiate it in any way, it would be *visible*, which it is not. As it can not be differentiated in any way, the *mind* seems to extend the general ground color of the neighboring field of view over it. This is, however, a psychological rather than a visual phenomenon. It is for a similar reason that it is impossible to see any limit to the field

of view, except where it is limited by the parts of the face, as nose, brows, etc. There is a certain limit horizontally outward where vision ceases, but it is impossible to detect any line of demarcation between the visible and the invisible.

But if we can not *see* the representative of the blind spot—i. e., the invisible spot—we can under certain conditions detect its *exact place* in the field. The phenomenon now about to be described can not be seen during the day when the retina is constantly stimulated, and therefore less sensitive, but may be easily observed on waking up in the middle of the night, or in early morning when the retina is exceptionally sensitive.

*Experiment 5.*—If on first waking in the morning the lids be closed and the eyes be turned quickly and strongly to one side or the other, as if to look at a point on the extreme verge of the visual field, two brilliant circles of radiating lines surrounding each a blank space are momentarily seen flashing out in the dark field on each side of the point of sight. On turning the eyes strongly in the opposite direction they again flash out on the dark field on the other side, at the moment of extreme strain of the ocular muscles. The phenomenon is especially brilliant if the visual plane be lowered or turned toward the feet. In Fig. 32, the curve represents the spatial concave. The eyes are shown turned strongly to the right and directed on *Ps*, the point of sight with the bright circle on each side. The dotted lines show position of the eyes turned to the left and the place of the bright circles.

The phenomenon is really extremely brilliant and conspicuous; but on account of its flashing momentariness, and still more on account of the position of the circles a little removed from the point of sight, where

alone form is given accurately, it is difficult to make an exact picture. In Fig. 32, I give it as nearly as I can.

Now there can be no doubt that we have here indicated the exact place of the invisible spot. The blank spaces from which the bright rays diverge are the

FIG. 32.

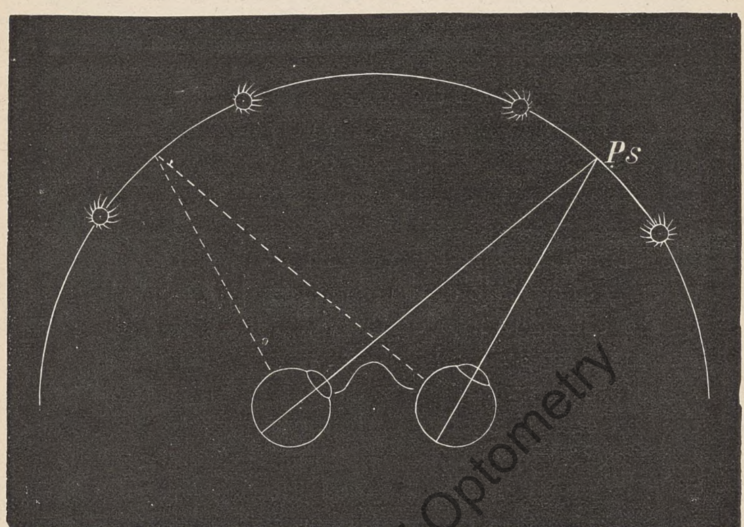



DIAGRAM SHOWING PLACE OF THE INVISIBLE SPOTS IN THE FIELD OF VISION.

representatives of the blind spots or places of entrance of the optic nerves, and the circles of bright rays are the representatives of the immediately surrounding bacillary layer. The parts surrounding the invisible spot are differentiated both from it and from the general field of darkness, and thus the place of that spot is exactly indicated. The cause of the phenomenon is obviously the strain on the optic nerves by pulling and bending, in the quick and violent turning of the eyeballs.

Two bright circles are seen, one on each side of the point of sight. One belongs to each eye. Which belongs to which? The answer to this question belongs to binocular vision; but we will say now in passing that since the entrance of the optic nerve is on the nasal side of the central spot, and since, as we shall see later, (page 116), impressions on the two nasal halves of the retinæ produce homonymously double images, in this case the bright circle on the right of the point of sight belongs to the right eye and that on the left to the left eye always. I find, in looking to the right, the left circle, and to the left, the right circle is the more brilliant.

---

## SECTION III.—COLOR PERCEPTION.

Thus far we have spoken of the perception of light so far as concerns brightness or intensity and direction. We come now to speak of the perception of light as *color*.

**Intensity versus Color.**—As there are two kinds of perception of sound—viz., simple sound or sound as *noise*, loud or faint, and sound as *tone* or musical pitch, high or low—so there are two kinds of perception of light—viz., light as *intensity* or brightness or shade, and light as *color*. In both sound and light, the one is a question of strength of vibration or wave-height, the other of rate of vibration or wave-length. The range of perceptible vibrations in the case of hearing or tones is very great, from ten to eleven octaves—i. e., from sixteen per second to thirty-two thousand per second; in the case of light or color only about one octave, for

the rate of vibration of an extreme violet ray is only about double that of an extreme red.

**Primary versus Secondary Colors.**—Again, we must distinguish between pure or *primary* colors and *mixed* or *secondary* colors. The primary colors are those which can not be made by any mixture of others, and are few in number. Secondary colors are such as can be so made, and are infinite in number. Again, pure colors may be mixed not only with one another, but also in all proportions with white and with black. The former mixtures have been called *tints*, the latter *shades*, or else all may be called shades. There is some difference of opinion as to which, and how many, colors should be called primary. This depends, partly at least, on the point of view, whether physical or physiological. Brewster made three primary colors—viz., red, yellow, and blue—regarding green as a mixture. Young and Helmholtz, and most physicists, make also three; but they are red, green, and violet, regarding yellow as a mixture. Brewster rejected green because of the well-known fact that purest pigment-blue mixed with purest pigment-yellow makes a fine green. True enough; but the superposition of the yellow of the spectrum on the blue of the spectrum does not make green. On the contrary, they kill one another and make a gray. This is really the true test, for pigments are never pure colors. Both chrome yellow and ultramarine blue contain green. When they are mixed, the yellow and blue kill one another, and the green of both comes out. On the other hand, all the later physicists rightly reject yellow because this color *is* made by the superposition of spectral red and spectral green. From the physical point of view, therefore, green and not yellow is a primary color. From this point of view the three primary

colors may be regarded as spread out, each over the whole spectrum, but in greatest abundance the red at one end, the violet at the other, and the green in the

FIG. 33.

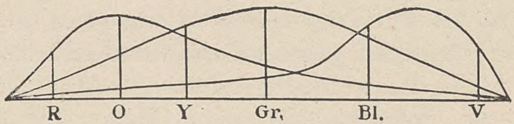



DIAGRAM SHOWING THE DISTRIBUTION IN THE SPECTRUM OF THE THREE PRIMARY COLORS OF YOUNG AND HELMHOLTZ.

middle, as shown in the diagram (Fig. 33).* The intermediate colors as seen are mixtures by overlap.

Hering takes up the subject from a wholly different point of view—physiological instead of physical. He investigates colors as sensations without reference to any physical considerations. From this point of view he makes six primary color-sensations essentially distinct from one another—viz., white, black, red, yellow, green, and blue. Or, if we relegate white and black to the category of shades instead of colors—of intensity instead of quality, for which we will give reasons hereafter—then by Hering's view there are four primary color-sensations—viz., red, yellow, green, and blue. Now, it can not be denied that from the pure point of view of sensation, unplagued by any physical considerations, Hering is right. Red, yellow, green, and blue are certainly perfectly distinct color-sensations irresolvable into any others or mixture of others, and they are the only colors thus irresolvable. This was recognized

* Helmholtz, in his latest utterances, adopts extreme blue instead of violet as the upper primary. (Stevens, vice-president's, address, p. 19, A. A. A. S., 1895.) His three primaries are carmine red, yellowish green, and ultramarine blue.

long ago by Leonardo da Vinci.* In orange and scarlet we distinctly see both red and yellow; in purple we see blue and red; and even in violet, one of the primaries of the physicists, we see distinctly blue with a glow of red. Further, Hering draws attention to the fact that his primaries consist of two pairs (or three pairs if we include, as he does, white and black) of complementaries which by mixture destroy one another—viz., red-green and yellow-blue. The importance of this in Hering's theory will be seen hereafter.

We have taken white and black out of the category of colors. Hering is undoubtedly right in regarding these as distinct sensations, irresolvable into any other or mixture of others, but not as *color*-sensations. Black to the physicist is a negation of light, but it is a very positive sensation to consciousness and entirely different from darkness; so also white is a perfectly pure sensation. We indeed know that, physically, white is produced by a mixture of all the spectral colors, but we do not see these in white. But, although it is indeed true that white and black are pure sensations, yet I do not think that color is the proper word for them. As a mixture of all rates of aërial vibrations produces noise, not musical tone, so a mixture of all rates of ethereal vibrations produces white, not color. Therefore it is best to put white and black out of the category of colors into that of intensity or shades; and from this point of view, since shades are of every grade, we may speak of all shades from white to black as one sensation—viz., gray.

**Theories of Color Perception.—General Account.**—1. The perception of color is a simple perception, incapable of analysis, and therefore is doubtless connected

* "Science," vol. i, p. 472, 1895.

with retinal structure of some sort. 2. Further, there is much reason to believe that it is an endowment of the cones, but not of the rods—that the rods perceive light only as light or intensity, not as quality; or more specifically that the rods perceive white and black and all shades of gray between, but not colors. The cones perceive all shades also, but, in addition, colors. The reason for believing so is as follows: As already said (page 55), the bacillary layer in the central spot consists of cones only, and in going thence outward in all directions the cones become less and less numerous among the rods until at the anterior margin of the retina there are no cones at all, but only rods. Now, as the representative of these facts in the field of view, we find that the perception of color is most perfect at the point of sight, and becomes less and less so as we go outward in all directions, until, on the extreme margins of the field of view, it is wholly wanting. In other words, the distribution of color perception in the field of view corresponds perfectly to the distribution of the cones in the retina.

Again, 3, it is further believed that color is perceived by means of some kind of physical response to light-vibrations of different rates, and the simplest conception, and that which was first adopted, is of responsive vibration on the part of the cones of the retina. Musical pitch is perceived by responsive vibrations of the rods of Corti, which have graduated lengths like the strings of a piano, adapted to co-vibrate, each with its own pitch. So it has been supposed that different cones, or possibly, as suggested by Stanly Hall, different parts of the same cone, are structurally adapted to co-vibrate with different rates of ethereal vibration, and give rise to different sensations of color.

This is the simplest conception of the process; but it is now far more probable that it is due rather to a photo-chemical change in a peculiar substance or peculiar substances, which we may call color-substances * in the cones. As the iodized plate, so these color-substances in the retina are differently affected by light of different rates of vibration.

The general theory given above is universally accepted; but when we attempt to express more definitely the physical correspondent of the perception of different colors, then our theory becomes more hypothetical. There are several such special theories. They are acceptable in proportion as they explain the phenomena.

**Young-Helmholtz Theory.**—According to the Young-Helmholtz theory of three primary colors, there are three distinct kinds of retinal cones, which respond re-respectively to three rates of ethereal vibration, and give rise to the perception of the three primary colors. If the vibrations are of such rate as to find response in only one kind of cone, we have pure color; but if of intermediate rates so as to affect two kinds we have mixed colors; if they affect equally all kinds, we have white. Or else we may say that there are three color-substances, each photo-chemically sensitive to one of the three primary colors, but when two kinds or all kinds are affected, they give rise to mixed colors or to white of various shades or grays.

**Hering's Theory.**—Leaving out, for reasons already given, white and black from the category of colors, according to Hering, in the retinal cones are found two kinds of color-substance, each of which is photo-chemically affected in two opposite ways, viz., by decompo-

* Observe, not colored substances but color-substances, i. e., substances which by photo-chemical change produce the sensation of color.

sition and recomposition—by destruction and restitution, by katabolism and anabolism. These two color-substances by opposite affections give rise to two pairs of complementaries, one to red-green and the other to yellow-blue; and the essential nature of complementariness, especially their mutual destructiveness, is thus easily explained. This accords well also with the artist view of colors embodied in the terms warm

FIG. 34.

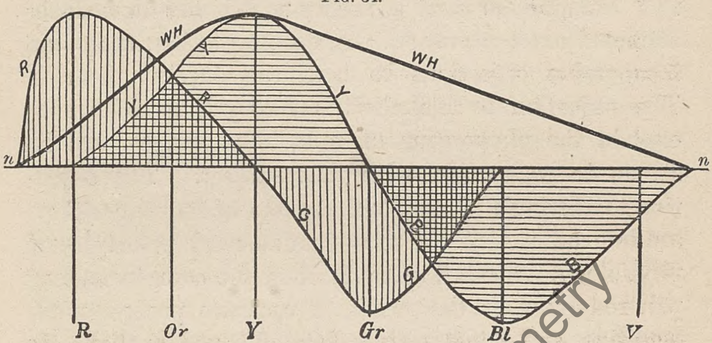



DIAGRAM TO ILLUSTRATE HERING'S THEORY OF COLOR VISION.—*R G* = red-green; *Y B* = yellow-blue, strong line; *W H* = white. (After Foster.)

(red and yellow) and cool (green and blue), the one more fatiguing because destructive, the other more restful because restitutive. Fig. 34, taken from Foster, is an attempt to graphically represent Hering's view. The horizontal line *n n* represents the extent of the visible spectrum. The places of the spectral colors are represented by the vertical lines from the letters *R*, *Or*, *Y*, *Gr*, *Bl*, *V*. The vertically lined space represents the affections of the red-green substance, and the horizontally lined space the affections of the yellow-blue substance. In each the space above the horizontal line *n n* shows katabolism or positive work or decomposi-

tion ; and the space below, anabolism or negative work or restitution. The strong line *wh wh* shows the distribution of light irrespective of color, i. e., white light throughout the spectrum. This line is supposed to show the affections of the so-called white-black substance, but it can express only katabolic and not anabolic changes, and therefore white only, not black, except as absence of light.

**Mrs. Franklin's Theory.**—Mrs. Franklin has recently * brought forward a theory which has deservedly attracted much attention. According to her, there are insuperable objections to both the current theories. The objection to Helmholtz's theory is its failure to explain the phenomena of color-blindness, as will be shown in connection with that subject. The objection to Hering's theory is that some of its suppositions are in conflict with the most fundamental principles of physiology. According to Hering, the complementary pair red-green is the result of opposite processes, destructive and constructive, katabolic and anabolic, in the same color-substance; and so also of the pair yellow-blue. Therefore activity or energy (for surely there is some energy expended in the perception of green or blue) may be generated by re-composition, reconstruction, anabolism. But it is a fundamental principle in physiology that vital energy is produced always at the expense of tissue—is generated always by katabolism. Constructive work does not and can not create but only consume, can not set free but only absorb energy. Negative energy seems a contradiction in terms. To the physiologist this will seem a fatal objection. But perhaps the psychologist may ask :

* "Zeitschrift für Psych. und Physiol. der Sinnesorgane," B. J. IV, 1892. "Mind," vol. ii, p. 473.

"May there not be definite states of consciousness corresponding also to restitutive processes? Are states of consciousness necessarily associated with expenditure of energy?" So much for the objections to other theories. Now her own.

Mrs. Franklin * supposes that there exists in all parts of the retina a fundamental visual substance which by photo-chemical change affects the retina in such wise as to produce the sensation of white of all shades, and which therefore may be called gray substance. This is always present in all parts of the retina, and in the history of the evolution of the eye was, at first, the only one. In the cones, but not in the rods, some of this substance is differentiated at first into two color-substances, yellow and blue, and finally into three color-substances, red, green, and blue, some of the yellow substance having been secondarily differentiated into red and green substances. Mixed colors, as in other theories, are due to simultaneous affections of two or more color-substances in varying proportions. Sunlight decomposes all in proportions exactly corresponding to the composition of the gray substances, and therefore produces the same sensation—in fact, may be said to reconstitute the gray substances. Yellow light decomposes the red and green substance in proportions corresponding to the original composition of the yellow substance; in fact, may be said to reconstitute the yellow substance, and therefore produces the same sensation. Thus the perception of white or gray may be due either to photo-chemical change in undifferentiated gray substance, as is doubtless the case in the rods, or to decomposition of all the color substances in propor-

* I give Mrs. Franklin's theory substantially as I understand it. In the attempt to make it clear, I have left out many details.

tions reconstituting gray substances, as is probable in the cones. Similarly the perception of yellow may be due either to photo-chemical change of some undifferentiated yellow substance, or else to the decomposition of the red and green color-substances in proportions reconstituting yellow substance. Both white or gray and yellow would on this view be primary sensations, because they were, and still are largely due to the decomposition of original substances.

### *Color-blindness.*

The defects of the eye already treated in Chapter II, Section II, are defects of the image-forming instrument; color-blindness is a defect of the receiving plate, a defect of retinal structure. As before we treated first the structure of the normal instrument, and then of its defects, so now, having given the supposed normal retinal structure, we come to treat of its defects.

**What is Color-blindness?**—Many persons lack a nice discrimination of colors and their shades. Such persons may see colors perfectly well, but from want of attention and culture, and especially for want of any accepted standard of colors and their names, have not learned to discriminate and name them. This must not be confounded with color-blindness. The color-blind do not see some colors at all as colors, but only as shades. The defect is not one of culture but of sensation, and therefore of retinal structure. An example will make this plain. In the commonest form of this defect, the sensations of red and green are wanting. To such a person the bright-green leaves and bright-red berries of a cherry orchard in full fruit, or red flowers and the green lawn on which they grow, would seem nearly or quite of the same tint, and neither of

them red or green, but both of them gray. The orchard or lawn would present the same appearance to their naked eyes as would its stereograph viewed in a stereoscope to the normal eye. For the iodized plate too is color-blind.

A comparison, again, of the eye and ear in this regard is instructive. The limits of perception of sound-vibrations are very wide, viz., sixteen per second to more than thirty-two thousand per second, or about eleven octaves; the limits of perception of light-vibrations are very restricted, only about one octave. Now, in some ears the extreme limit is not perceived, but this is not considered a grave defect, for there is no special use for the extremest range. In the eye, too, the extreme limits, though so narrow, are sometimes not reached, but in this case the usefulness of the whole range makes this a serious defect. This is color-blindness. In the ear the vibrations most commonly unperceived are at the upper end of the scale. In the eye the defect is usually at the lower and middle parts of the scale; red or red and green are unperceived. The red-green blind see yellow and blue perfectly well.

But between the ear and eye there is this fundamental difference: In the case of the ear the defect of perception on the extreme limit of range is one not only of pitch, but also of sound; while in the case of the eye it is only of color, and not at all of light. This shows a probable essential difference in the nature of the response in the two cases.

**Explanation of Color-blindness.**—The severest test of the theories of color perception is their application in the explanation of color-blindness. The general theory of this defect is, that one or more of the normal ret-

inal elements or retinal color-substances is wanting. Let us try the several theories by this test.

1. **Helmholtz's Theory.**—Perhaps the most commonly wanting of all colors is red. According to this theory the defect in these cases consists in the absence of the red color-substance. The normal eye is trichromic, the red-blind eye is dichromic. Now, it is certainly true that the color-blind eye is dichromic; but, as first pointed out by Pole, who is himself color-blind, the two colors seen are not usually green and blue or violet, as it should be on this theory, but *yellow* and blue or violet.* The most common of all forms of color-blindness is red-green blindness. These persons see yellow perfectly well. But if yellow be not a primary color, but a mixture of red and green, how is it that yellow is seen? Again, according to this theory the sensation of white is due to the photo-chemical affection of all the three primary color-substances. How, then, can color-blind persons see white when one or more of its constituents are wanting? † For that they do see white as normal eyes do, is proved by cases in which one eye only is color-blind. In such cases the two eyes used alternately see white exactly alike. The great objection to Helmholtz's theory, then, is the normal perception of yellow when both its constituents are wanting, and of white when one or more of its constituents are wanting.

2. **Hering's Theory.**—Once admit that perception can result from restitutive processes, and Hering's theory

* Nature, vol. xx, pp. 477, 611, 637, 1879; Contemporary Review, May, 1880.

† The red-blind by this theory ought to see white as a bluish green, as normal eyes do when the red substance is exhausted by gazing intently on a red spot and then turning the eyes on a white sheet. Under these conditions the normal eye is temporarily red-blind.

of color perception explains the phenomena perfectly. According to him, in cases of red-green blindness (the commonest of all) the red-green substance is wanting, while the yellow-blue substance is present. It is inevitable according to this theory that complementaries should be wanting together. Accordingly we do find cases of yellow-blue blindness, although they are rare. The perception of white, of course, presents no difficulty, because, according to him, white and black are primary complementaries due to a peculiar substance which seems never to be wanting. The real objections to Hering's theory are of another kind, already mentioned.

3. Mrs. Franklin's theory explains the phenomena well. In the gradual evolution of the eye from earliest times and from lowest animals to its present perfected condition, (1) first only gray substance was present, and therefore only white and black and all shades of gray were seen. This, as a primitive condition, is *a priori* almost certain. (2) Then this primary visual substance was differentiated into two color-substances, yellow and blue; and therefore these two colors, together with white and black and gray, were all that were seen. (3) Then, finally, the yellow color-substance was secondarily differentiated into red and green color-substances, which produce respectively these colors, but still by their combination may reconstitute yellow substance and produce the sensation of yellow in the normal eye, precisely as the combination of all may reconstitute gray substance and produce the sensation of white or gray. Now, according to Mrs. Franklin, color-blindness, like so many other defects in the animal body, is an example of atavism—i. e., a return to primitive conditions. Complete color-blindness (which

sometimes, though rarely, occurs), in which no colors of any kind are seen, but only white and black and shades of gray, is the result of complete atavism, or a return to Stage 1. Red-green blindness, the most common of all, is a return to Stage 2. Of course, Stage 3 is the normal and most common condition. There are other forms of color-blindness—for example, yellow-blue blindness—which can not well be explained by this theory, although easily by Hering's. But this form is very rare, and may be a defect in the cortical substance of the brain.

In further justification of this view it may be urged (1) that the "law of differentiation" is the most universal law of biological evolution, and therefore it is almost certain that retinal structure and visual substance, like all else, is subject to this law. (2) That the evolution of the ear and the sense of hearing seems to have followed a course analogous to that attributed to the eye and the sense of sight. As in the evolution of the ear, the labyrinth (vestibular sac and semicircular canals) was first developed, and then the cochlea, and therefore sound was perceived first only as noise, and then also as tone, so in the evolution of the eye the rods were first developed, and then the cones; and therefore light was perceived first as white and shades, and then as colors.

**What the Color-blind really see.**—We are now in position to explain what the color-blind really see. The completely color-blind see a landscape with all its colors of earth and sky precisely as the stereograph of the same landscape is seen in a stereoscope by the normal eye. He sees shades, but not color. But this case is rare. As there are various kinds and degrees of color-blindness, we will take only the most common kind,

viz., red-green blindness. In persons affected with this too common defect, some colors are seen perfectly correctly, some incorrectly, and some not at all as colors, but as shades. Of pure colors, what they see at all they see correctly, the rest they see only as shades. The mixed colors they always see incorrectly. We give below a schedule showing what the red-green blind see. It will be observed that in their color-scheme there is a great predominance of browns and slate-blue.

PURE COLORS.

*I. See correctly.*

*a.* White and black and all intermediate shades or grays.

*b.* Yellow and all shades of the same, i. e., browns.

*c.* Blue and all shades of same or slate-blues.

*II. Don't see at all as Colors.*

*a.* Reds are seen as different shades of gray.

*b.* Greens are seen as different shades of gray.

MIXED COLORS.

*III. See incorrectly.*

*a.* Scarlet = red and yellow: are seen as gray and yellow = dark brown.

*b.* Orange = red and yellow: are seen as gray and yellow = lighter brown.

*c.* Purples = red and blue: are seen as gray and blue = slate-blue.

*d.* Yellowish green = yellow and green: are seen as yellow and gray = brown.

*e.* Bluish green = blue and green: are seen as blue and gray = slate-blue.

### *Tests for Color-blindness.*

The phenomena stated in the above table are apparently so conspicuous that it seems almost incredible that persons should be color-blind unknown to themselves and their friends. Yet nothing is more certain than that even intelligent persons may have this defect without being at all aware of it. They use the terms red, green, etc., although the sensations corresponding to these terms are different from those experienced by persons of normal eyes. But how are they to know it? They may make strange and unaccountable mistakes sometimes, but these are attributed to the loose use of color-names. The defect is by no means uncommon, and, what is worthy of note, it is far more common among men than among women. Among men perhaps four to five per cent are more or less color-blind; among women hardly more than one tenth per cent. The importance of testing for this defect in the case of engine-drivers and switchmen of railways, and wheelmen and lookouts of vessels, can not be overestimated. There are many methods of testing, some of them very refined and accurate; but for that very reason unadapted for ordinary use. The simplest, and perhaps one of the best, is that of Holmgren. A box full of skeins of yarn of all colors and shades is placed before the subject, and he is directed, without assistance, to sort and match them. All normal-eyed persons will match them similarly and correctly, but in the case of the decidedly color-blind the most extraordinary matchings occur. For example, bright reds and bright greens and certain shades of gray, or scarlet and certain shades of brown, or splendid purples and certain shades of slate-blue, are put together as the same color and shade.

# PART II.

# BINOCULAR VISION.

---

## CHAPTER I.

### *SINGLE AND DOUBLE VISION.*

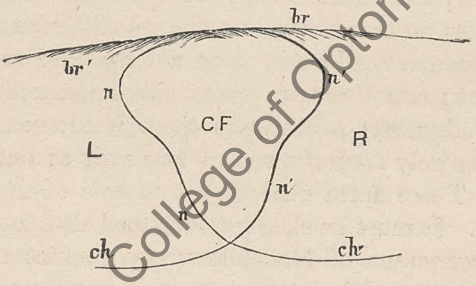
**The Two Eyes a Single Instrument.**—We have thus far treated only of the phenomena of monocular vision; and all that we have said might still apply, almost word for word, if, like the Cyclops Polyphemus, we had but one eye in the middle of the forehead. But we have two eyes; and these are not to be considered as mere duplicates, so that if we lose one we still have another. On the contrary, the two eyes act together as one instrument; and there are many visual phenomena, and many judgments based upon these phenomena, which result entirely from the use of two eyes as one instrument. These form the subject matter of *Binocular Vision*. It must be clearly understood that the distinctive phenomena of binocular vision require two eyes acting as one. We might have two eyes, or even, like Argus, a hundred eyes, and yet not enjoy the advantages of binocular vision; for each eye might see independently. This would still be monocular vision.

The phenomena of binocular vision are far less purely physical than those of monocular vision. They

are also far more obscure, illusory, and difficult of analysis, because far more subjective and far more closely allied to psychical phenomena. From early childhood I have amused myself with experiments in this field, and have thus acquired an unusual voluntary power over the movements of the eyes, and a still more unusual power of analysis of visual phenomena. This has always therefore been a favorite field for me; but with a little practice any one may acquire similar power and enjoy a similar pleasure.

**Binocular Field.**—We have said that the field of view is naught else than an outward projection of retinal states. With the eyes open and the retina in an active or stimulated condition, we call it the *field of view;* with the eyes shut and the retina in a comparatively passive or unstimulated condition, we call it the *field of darkness.* In either case, every variation in the state of different parts of the retina, whether by

FIG. 35.




shadows or by images, or by its own internal changes or unstimulated activity, is faithfully represented in external space by spectra, external images, etc. But we have *two* eyes, and therefore two retinæ, and therefore also two fields of view, the external projections of

the two retinæ. These two fields of view partly overlap each other, so as to form a common or binocular field. Fig. 35 represents roughly the form of these fields in my own case. The right field, *R*, is bounded by the line of the nose *n n* on the left, the brows *br* above, and the cheek *ch* below. The field of the left eye, *L*, is bounded similarly on the right by the nose *n′ n′*, the brow *br′*, and the cheek *ch′*. Between the lines of the nose, *n n*, *n′ n′*, is the rounded triangular space *C F*, which is the common or binocular field. This common field is the only part seen by both eyes. The two fields are left vacant on the extreme right and left, because, projected on a plane surface, they are unlimited in these directions. This is the necessary result of the fact that in a horizontal direction the field of view of both eyes is more than 180°.

Now, there being two retinæ, there are of course two retinal images of every external object; and since retinal images are projected outward into space as external images, we must have *two external images* of every object. But we see objects only by these external images. Why, then, with two retinal images—ay, and two external images for every object, do we not see all objects *double?* I answer: *We do indeed see all objects double, except under certain conditions.*

### *Double Images.*

This phenomenon of double images of all objects, except under certain special conditions, is so fundamental in binocular vision, and yet so commonly overlooked by even the most intelligent persons unaccustomed to analyze their visual impressions, that it becomes absolutely necessary first of all to prove it by detailing many experiments, which every one may repeat for himself.

*Experiment 1.*—Holding up the finger before the eyes, look, not at the finger, but at the wall or the ceiling or the sky. Two transparent images of the finger will be seen, the left one belonging to the right eye and the right one to the left eye. We easily prove this by shutting first one and then the other eye, and observing which image disappears. The images are *transparent*, or shadowy, because they do not conceal anything. The place covered by the right-eye image is seen by the left eye, and the place covered by the left-eye image is seen by the right eye. If we alternately shut one eye and then the other, the wide difference between these places is at once evident. Usually there is an alternation in the distinctness of these shadowy images—first one and then the other fading away, and almost disappearing from view. Many persons find difficulty in consciously recognizing the two images. Such persons habitually neglect one, until it finally drops out of consciousness—which one they neglect will be shown in the next experiment.

*Experiment 2.*—Point with the forefinger at some distant object, looking with both eyes open at the object, not the finger. Two fingers will be seen, one of them pointing at the object and the other far out of range, usually to the right.

Most persons find some difficulty at first in being conscious of perceiving two images. The reason is, they do not easily separate what they know from what they see. They *know* there is but one finger, and therefore they think they *see* but one. The best plan is to shut alternately one eye and then the other, and observe the places of projection of the finger against the wall; and then, opening both eyes, shadowy images at both these places will be seen. I have found

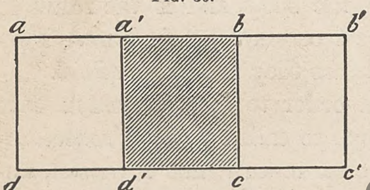
some trouble in convincing a few persons, and have found one single person whom I could not convince, that there were two images. To such a person all that I am about to say on binocular vision will be utterly unintelligible. The whole cause of the difficulty in perceiving at once double images is, that we habitually neglect one image unless attention is especially drawn to it. I have found that nearly all persons neglect the right-hand image—i. e., the image belonging to the left eye (unless the right eye is defective). In other words, they are *right-eyed* as well as right-handed. I have also tried the same experiment on several left-handed persons, and have found that these neglected the left image—i. e., the image belonging to the right eye. In other words, they were *left-eyed* as well as left-handed. There is no doubt that dextrality affects the whole side of the body, and is the result of greater activity of the left cerebral hemisphere. People are right-handed because they are *left-brained*.

I pause a moment in order to draw attention here to the uncertainty of some so-called *facts of consciousness*. I have often labored to convince a person, unaccustomed to analyze his visual impressions, of the existence of double images in his own case. He would appeal with confidence, perhaps with some heat, to his consciousness against my reason; and yet he would finally admit that I was right and he was wrong. So-called facts of consciousness must be scrutinized and analyzed, and subjected to the crucible of reason, as well as other supposed facts, before they should be received.

*Experiment 3.*—Place the two forefingers, one before the other, in the middle plane of the head (i. e., the vertical plane through the nose, and dividing the head into two symmetrical halves), and separated by a

considerable distance—say one 8 inches and the other 18 to 20 inches from the eyes. Now, if we look at the farther finger, it will be of course seen single, but the nearer one is double; if we look at the nearer finger, this will be seen single, but the farther one is now double; but it is impossible to see both of them as single objects at the same time. By alternately shutting one eye and then the other, we can observe in either case which of the double images disappears. Thus we will learn that when we look at the farther finger, the nearer one is so doubled that the left image belongs to the right eye and the right image to the left eye; while, on the contrary, when we look at the nearer finger, the farther one is so doubled that the right image belongs to the right eye and the left image to the left eye. In the former case the images are said to be *heteronymous*, i. e., of different name, and in the latter case they are said to be *homonymous*, i. e., of the same name, as the eye.

Fig. 36.




Showing Mode of Doubling of a Larger Object. — $a\ b\ c\ d$ = right-eye image; $a'\ b'\ c'\ d'$ = left-eye image.

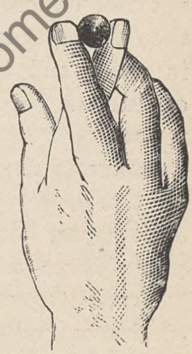
*Experiment 4.*—Instead of a narrow object like the finger, take next some object wider than the distance between the eye-centers—such as a postal card, for example—and repeat experiment 1. While we look at the wall the card doubles, but the double images do not entirely separate. There is a middle opaque overlapping part with shadowy transparent margins right and left (Fig. 36). In this figure $a\ b\ c\ d$ is the right-eye image and $a'\ b'\ c'\ d'$ the left-eye image. The overlapping part is opaque, because it covers a part of the wall

hidden from *both eyes.* The margins are transparent, because they cover portions of the wall hidden from one eye but seen by the other. As we gaze steadily we observe a sort of struggle between the two images for mastery. First perhaps the right-eye image prevails, the left-eye image disappearing and the right-eye image becoming opaque throughout. Then the left-eye image prevails and the reverse takes place.

There is a limit, therefore, to the separation of double images when we look beyond the object—i. e., in case of heteronymously double images. This limit is the *interocular space*, and the reason is that we can not turn our eyes outward beyond parallelism. There is no limit in the case of homonymously double images except the ability to converge the optic axes.

It is evident, then, that double images are formed whenever the optic axes are not turned directly on the object observed. For example: if the finger be pressed in the corner of one or both eyes we see double images. If it is the external corner, the images are heteronymous; if the internal corner, they are homonymous.

Fig. 37.



**Analogues of Double Images in Other Senses.**—Whenever it was possible, we have traced the analogy of visual phenomena in other senses. Is there any analogue of double vision to be found in other senses? There is, as may be shown by the following experiment: If we cross the middle finger over the forefinger until the points are well separated, and then roll a small round body, like a child's marble, about on the table between the points of the crossed fingers, we will dis-

tinctly perceive two marbles. The points of the fingers touched by the marble are unaccustomed to be touched in that way—they are non-corresponding. (Fig. 37.)

**Single Vision.**—Therefore it is evident that when we look directly at anything we see it single, but that all things nearer or beyond the point of sight are seen double. We then come back to our previous proposition, that we always see things double except under certain conditions. What, then, are the conditions of single vision? I answer: *We see a thing single when the two images of that thing are projected outward to the same spot in space, and are therefore superposed and coincide.* Under all other conditions we see them double. Again: the two external images of an object are thrown to the same spot, and thus superposed and seen single, when the two retinal images of that object fall on what are called *corresponding points* (or sometimes identical points) *of the two retinæ.* If they do not fall on corresponding points of the two retinæ, then the external images are thrown to different places in space, and therefore seen double. We must now explain the position of corresponding points of the two retinæ.

**Corresponding Points.**—The retinæ, as already seen, are two deeply concave or cup-shaped expansions of the optic nerve. If $R$ and $L$, Fig. 38, represent a projection of these two retinal cups, then the black spots $C\ C'$, in the centers of the bottom, will represent the position of the central spots. If now we draw vertical lines (vertical meridians), $a\ b$, $a'\ b'$, through the central spots, so as to divide the retinæ into two equal halves, then the right or shaded halves would correspond point for point, and the left or unshaded halves would correspond point for point; i. e., the internal or nasal half of one

retina corresponds with the external or temporal half of the other, and *vice versa*. Or, more accurately, if the concave retinæ be covered with a system of rectangular spherical coördinates, like the lines of latitude and longitude of a globe, $a\,b$ and $x\,y$ being the meridian and equator, then points of similar longitude and latitude in the two retinæ, as $d\,d'$, $e\,e'$, are corresponding. Or, still better, suppose the two eyes or the two retinæ to be placed one upon the other, so that they coincide throughout like geometric solids; then the coincident points are also corresponding points. Or again: Take

FIG. 38.

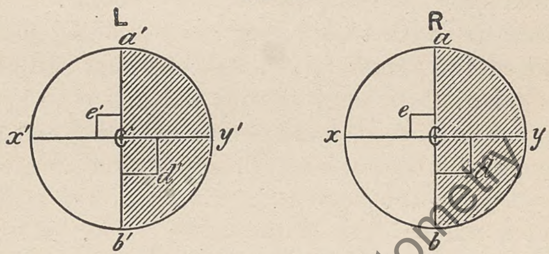



DIAGRAM SHOWING CORRESPONDING HALVES OF THE RETINÆ.

a pair of dividers and open the points until they are the exact distance apart of the central spots (interocular space). Then, holding level, suppose the two retinæ to be touched at many points. The points touched at the same time would be corresponding points. The mode of getting the interocular space is fully described on page 265. It is usually about two and a half inches. Of course, the central spots will be corresponding points; also points on the vertical meridians, $a\,b$, $a'\,b'$, at equal distances from the central spots, will be corresponding; also points similarly situated in similar quadrants, as $d\,d'$, $e\,e'$, etc. It is probable that the definition just given

is not mathematically exact for some eyes. It is probable that in some eyes the apparent vertical meridian which divides the retinæ into corresponding halves is not perfectly vertical, but slightly inclined outward at the top. This would affect all the meridians slightly; but the effect is very small, and I do not find it so in my eyes. We shall discuss this point again (page 218).

**Law of Corresponding Points.**—After this explanation we reënunciate the law of corresponding points: *Objects are seen single when their retinal images fall on corresponding points.* If they do not fall on corresponding points, their external images are thrown to different places in space, and therefore are seen double.

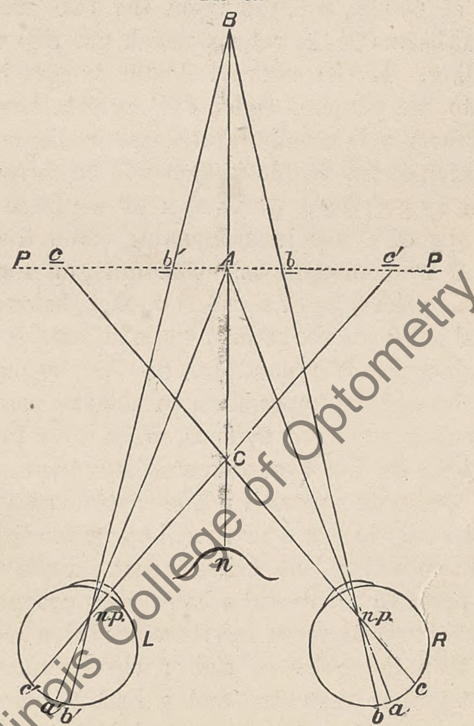
Thus we see that the term "corresponding points" is used in two senses, which must be kept distinct in the mind of the reader. Every rod and cone in each retina has its correspondent in external space, and these exchange with each other by impression and projection. Also every rod or cone of each retina has its correspondent in a rod or cone in the other retina. Now the law of corresponding points, with which we are now dealing, states that the two *external or spatial correspondents* of two retinal corresponding points *always coincide with each other*, or the corresponding points of the two retinæ *have the same spatial correspondent.* In order to distinguish these two kinds of corresponding points from each other, the latter—i. e., corresponding points on the two retinæ—are often, and perhaps best, called "identical points," because their external spatial representatives are really *identical.*

Thus, there is a kind of triangular correspondence between the retinæ and space. Every point in space has a correspondent in each retina, and the two retinal correspondents are an exact interocular distance apart;

but the place of these retinal correspondents change with every movement of the eyes. The images of spatial points, however, do not fall on their retinal correspondents except under certain conditions, viz., those which determine single vision.

*Application.*—We will now apply the law to the explanation of single and double vision. We have seen

FIG. 39.



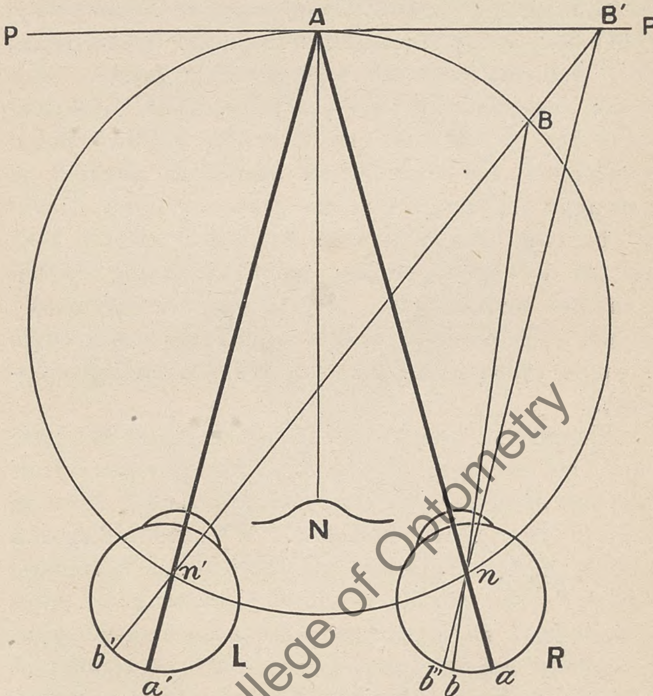

(experiment 1) that an object is seen single when looked at, but that all objects beyond or on this side the point of sight are doubled in opposite directions. Diagram

Fig. 39 shows why, by the law of corresponding points, it must be so. While the two eyes, *R* and *L*, are fixed upon *A*, this object will be seen single, for its images, *a* and *a′*, fall upon the central spots. But if, while still looking at *A*, we observe *B* and *C*, we shall see that both are double. The reason is, that the images of *B*, viz., *b b′*, fall upon the two nasal or internal halves of the retinæ, which are non-corresponding; while the images of *C*, viz., *c c′*, fall upon the two external or temporal halves of the retinæ, which are also non-corresponding. If the external double images be all referred to the plane of sight, *PP* (which, however, is not the fact), as is usually represented in diagrams, then the position of the double images will be correctly represented by $\underline{c}\ \underline{c}'$, $\underline{b}\ \underline{b}'$. It is seen at a glance that the images $\underline{c}\ \underline{c}'$ of *C* are heteronymous, while the images $\underline{b}\ \underline{b}'$ of *B* are homonymous. Generally, all the field of view within the lines of sight, *A a*, *A a′*, belongs to the temporal halves of the retinæ, while all outside of these lines belongs to the nasal halves. Or, again, double images formed by impressions on the two nasal halves of the retinæ are homonymous, while those formed by impressions on the two temporal halves are heteronymous. Or, more generally: The central spots are, say, two and a half inches apart. All corresponding points are also two and a half inches apart. Retinal images farther apart than two and a half inches produce heteronymous external images, and therefore belong to objects nearer than the point of sight; while retinal images nearer together than two and a half inches produce homonymous external images, and belong to objects farther away than the point of sight.

Thus far the objects considered are on the median line. Next we will consider those in other positions.

*Horopteric Circle of Müller.*—Objects at point of sight are seen single, while objects beyond or nearer than that point are seen double. But how is it with objects about the same distance as that point but not in

FIG. 40.




THE HOROPTERIC CIRCLE OF MÜLLER.—*R* and *L*, two eyes; *n n′*, point of crossing of ray-lines—nodal point; *A*, point of sight; *B*, some other point in the horoptoric circle *A n n′*; *a a′*, central spots; *a a′*, *b b′*, retinal images of *A* and *B*.

the median line—i. e., above or below, on the right or left? Take first the case of points lying to the right or left. In the diagram Fig. 40 the two eyes, *R* and *L*, are fixed on the object, *A*. This is, of course, seen single because its retinal images fall on corresponding

points, viz., the central spots. Now, if a circle be drawn through the point of sight, $A$, and through the nodal points, $n' n$, of the two eyes, then by simple geometrical construction it is evident that any point, $B$, lying in that circle will also be seen single; for its two retinal images, $b b'$, will fall on equivalent halves of the retina, and at equal distances from the central spots, $a a'$,* and therefore are corresponding points. This is the *horopteric circle of Müller.* The same will *not* be true of points on any other line whether curved or straight. For example, an object, $B'$, situated on a straight line tangent at the point of sight, $A$, will not be seen single, because its retinal images, $b' b''$, are not on corresponding points, $b''$ being farther from the central spot. It will be heteronymously double. The circle of Müller is probably a true circle of single vision when the eyes are not strongly converged.

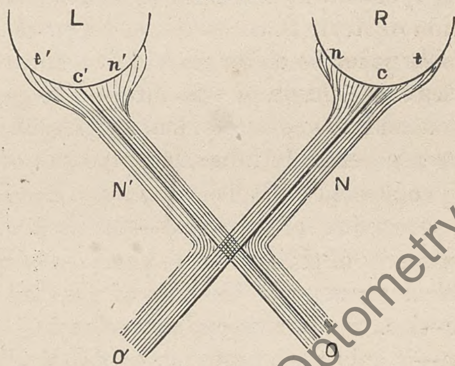
*Horopter or Surface of Single Vision.*—We have considered the case of objects lying right and left of the point of sight. We have yet to consider those in addition lying above or below. We have spoken of a possible horopteric *circle.* Is there also a horopteric *surface?* The *surface* of single vision with the point of sight fixed, or the surface passing through the point of sight all objects lying in which are seen single, is called *the horopter.* Whether there be such a surface at all, and if there is, what is its form, are questions upon which the acutest observers differ. Some have made it a plane, some a spherical surface. Some, by purely geometrical methods, have given it the most

* The angles $A\,n\,B$ and $A\,n'\,B$ are equal because they are angles at the circumference standing on the same arc $A\,B$. Their opposites, $a\,n\,b$ and $a'\,n'\,b'$, are therefore also equal.

curious forms and properties; while others, by purely experimental methods, have come to the conclusion that it is not a surface at all, but a *line*. We are not now prepared to discuss this question, but shall return and devote to it a special chapter.

**Supposed Relation of the Optic Chiasm to the Law of Corresponding Points.**—In the optic chiasm, Fig. 22, page 51, there is certainly a partial (but only a partial) crossing of the fibers of the two optic nerves. Many

FIG. 41.




*O O′*, optic roots; *N N′*, optic nerves; *R* and *L*, sections of the two eyes; *c c′*, central spots; *n n′*, the nasal halves, and *t t′*, the temporal halves, of the retinæ.

physiologists connect this fact with this remarkable law. There is probably such a connection. But many go farther. They think that some of the fibers of each optic nerve cross over to the other eye, and some do not; and that those which cross over supply the internal or nasal halves, and those which do not cross over supply the temporal halves. Thus, in the diagram Fig. 41, the fibers of the right optic nerve-root *O*, as it comes from the brain, go in part directly to supply the temporal half *t* of the right retina, and in part by crossing

the nasal half $n'$ of the left retina, and these are corresponding halves. So also the fibers of the left optic nerve-root $O'$ go to supply the temporal half $t'$ of the left and nasal half $n$ of the right retina. Still further, they think that the fibers coming from corresponding or identical points or rods or cones in the two retinæ are not only thus carried by the same optic root, but finally unite to form one fiber, or at least terminate centrally in one brain-cell, and thus form one single sense-impression. It is almost needless to say that, while this is an interesting speculation, it is nothing more; for the supposed union of fibers from corresponding rods or cones can probably never be either proved or disproved.

**Theories of the Origin of this Law.**—The perception of direction and the correspondence of retinal and spatial points are certainly inherent properties of the retina, being connected with its structure. The former—i. e., the perception of *direction*—we have seen, is a general property of sensory nerves, only developed into mathematical accuracy in the case of the optic nerve; the latter—i. e., the correspondence of retinal and spatial points—is only the expression of this mathematical accuracy of perception of direction; and both are connected with the structure of the bacillary layer. Undoubtedly, then, this property is innate and antecedent to all individual experience.* What the infant learns by experience is not direction, but distance and size of the object. Direction is a primary datum of sense (page 73). But the property of *corresponding points* of the two retinæ and of *identical spatial points* in the two fields of view seems to be less absolutely simple and primary. The question, "Is this property innate, in-

* It is probably the result of experience, but of ancestral experience, inherited by the individual.

stinctive, antecedent to experience? or is it wholly the result of experience?" has been long and hotly disputed by the profoundest thinkers on this subject. The former view has been held by Müller, Pictet, and others; the latter by Helmholtz, Brücke, Prévost, and Giraud Teulon; the one is called the *nativistic*, the other the *empiristic theory*.

We shall not follow the history of this dispute, nor detail the arguments brought forward on each side; for the tendency of modern science, under the guidance of the theory of evolution, is to bring these two opposite views together, and reconcile them by showing that they are both in a degree true, and therefore not wholly inconsistent with each other. The difficulty heretofore has been that anatomists and physiologists have studied man too much apart from other animals, and thus the amount of inherited, innate, instinctive qualities has been greatly underestimated by some and overestimated by others. A new-born chicken, in a few minutes after breaking the egg-shell, will see an object, direct the eyes upon it, walk straight up to it, and seize it. Evidently there is in this case not only a perception of direction, antecedent to all experience, but also some perception of distance, and the wonderful coördination of muscles necessary for standing and walking, and directing the movements of the eyes. A young ruminant animal in a few minutes after birth will stand and walk, and direct its motions by sight. A bird of wild species, hatched in a cage and kept in a cage until it is fully fledged and its muscles are sufficiently developed, if then thrown into the air, will fly away with ease, although the coördination of many muscles in the act of flying is something so marvelous that it could not be learned in a lifetime of trial, unaided by inherited

capacity. Inherited powers are still more marvelous in the case of insects.

Manifestly, then, the wealth of capacities in all directions possessed by the individual is partly inherited and partly acquired by individual experience. In animals the inherited, in man the individually acquired, wealth predominates. But all wealth is acquired. Even that inherited is ancestral experience accumulated and transmitted by the law of heredity. Even instinct is "inherited experience." Thus, then, it is evident that the property of corresponding points of the two retinæ, and therefore of identical points in space, is partly inherited and partly acquired by individual experience. It is doubtless wholly the result of experience, but not wholly of *individual* experience.

**Consensual Adjustments.**—There are therefore two adjustments of the eye in every voluntary act of sight, viz., *focal* and *axial*. In the former, *each eye* is adjusted by the ciliary muscle to make a perfect image on the retina; in the latter, the *two eyes* are turned by the recti muscles so that their axes shall meet on the point of sight, and the images of the object looked at shall fall on the central spots. The one is an adjustment for *distinct* vision, the other for *single* vision. There is associated with these still a third adjustment, but of far less importance, viz., the *adjustment of the pupil*. The pupil contracts and expands not only as the light is bright or faint, but also as the object is near or far. These three adjustments take place together and without distinct volition for each—i. e., by the one voluntary act of *looking*. They are therefore consensual movements, and usually regarded as indissolubly associated. We shall show hereafter that under certain circumstances they may be dissociated.

**The Two Fundamental Laws.**—There are also two great and fundamental laws by which all visual phenomena are explained, viz., the *law of direction* and the *law of corresponding points.* The one gives the true position of all points in space, and therefore entirely explains the apparent anomaly of erect vision with inverted retinal images; the other gives coincidence of the spatial representative of corresponding points in the two fields of view, and therefore entirely explains the second anomaly of vision, viz., of single vision with two retinal images. Both may in fact be called laws of corresponding points. The one asserts the correspondence point for point of retinal rods and cones with external space, with ray-lines connecting and crossing in the nodal point; the other asserts a correspondence point for point of the rods and cones of the two retinæ, and the coincidence of their representatives in the two fields of view. From the one law flow all the phenomena of *monocular*, from the other all the phenomena of *binocular* vision. But underlying both of these is the still more fundamental law of external projection of retinal states.

All the phenomena of binocular vision are explained by the law of corresponding points. But the phenomena are so numerous, so illusory, and so difficult of analysis, that the connection is by no means obvious. The science of binocular vision consists in tracing this connection, and thus explaining the phenomena. It will be our object, then, to take up all the most important phenomena of binocular vision, and explain them in this way.

## CHAPTER II.

### *SUPERPOSITION OF EXTERNAL IMAGES, AND THE FORMATION OF PHANTOMS.*

In the movements of one eye, or of the two eyes if they move together equally in the same direction, as in looking to one side or the other, or up or down, objects seem to *stand still*, and the eyes or the point of sight to *sweep over them.* But if we move the eyes in opposite directions, as in converging the optic axes strongly and then allowing them to become again parallel, objects, or rather their external images, seem to sweep like trooping shadows across the field of view; or rather, the fields of view themselves seem to rotate, carrying all their images with them, in a direction contrary to the motion of the eye, and therefore (since the two eyes move in contrary directions) in directions contrary to each other. This phenomenon is not very easily observed, because it is best seen by simple convergence of the eyes on a very near point in space, without any object to direct the convergence, or in trying to look at the root of the nose. Divergence of the eyes may be produced by pressing the fingers in their external corners. In this case also the motion of the images is evident.

Evidently, then, by voluntary motion of the eyeballs in opposite directions, and the consequent motion of the

shadowy images in opposite directions, we may (if we observe the images and control the motion of the eyes) cause them, whether they belong to the same object or to different objects, to approach each other and combine successively. Many curious phenomena thus result which it is necessary to understand before we approach the more complex phenomena, and especially before we can explain the judgments based upon these phenomena.

**Combination of the Images of Different Objects.**—We have seen that the combination of the two external images of the *same* object produces single vision. But the external images of *different* objects may also be combined. Under this head there are several cases.

1. **Dissimilar Objects.**—We have seen that when the two images of an object fall on corresponding points of the two retinæ, they are thrown outward as external images to the same point in space, superposed, and united, and therefore the object is seen single. If, instead of the two images of the same object, the images of two different objects fall upon corresponding points, evidently they also will be thrown to the same place in space and superposed. In this case, however, there being two objects, there will be four retinal images, only two of which will fall on corresponding points, and also four external images, only two of which will be superposed. But we may confine our attention to the superposed images, or else we may cut off the others from view, or prevent them from forming.

*Experiment 1.*—If the left hand and the right forefinger, or any two dissimilar objects, be held up before the eyes, say 8 to 10 inches apart, and then the eyes be converged until the right eye looks exactly toward the left hand and the left eye toward the right forefinger,

then evidently the retinal images of these two objects will fall on corresponding points, viz., on the *central spots;* and their corresponding external images ought to be thrown to the same place and superposed. Such is actually the fact. The phenomena as they actually appear are as follows: As the eyes begin to converge, the images of both objects double homonymously, and we see now four images. As the convergence increases, the double images separate more and more, until the left image (belonging to the left eye) of the forefinger and the right image of the hand (this belongs to the right eye) are brought together and superposed, and the forefinger is seen lying in the palm of the hand. Of course, as already explained, there will be two other images—one of the forefinger to the right, and belonging to the right eye, and one of the hand to the left, and belong to the left eye. By shutting alternately one eye and then the other, these belongings of the several images may be tested.

*Experiment 2.*—Or, again, the same combination may take place without convergence of the eyes, thus: Hold up the two forefingers before the eyes a foot or so distant, and a little more than two inches apart (it should be nearly equal to the interocular distance), and against a bright background like a white wall or the sky. Now look at the wall or the sky: the two fingers will both double, making four images; but the two middle images will unite to form what seems to be one finger. There will be therefore apparently three images: the middle one (the combined images) is opaque like an object; the other two, uncombined, are transparent like ordinary double images. In this case, as we are gazing beyond the finger, the double images are heteronymous. It is therefore the right-eye image of the

right finger (the left of its double images) and the left-eye image of the left finger (the right of its double images) which combine in the middle.

These facts and the conditions under which the combination takes place are illustrated by the accompanying diagrams.

FIG. 42.

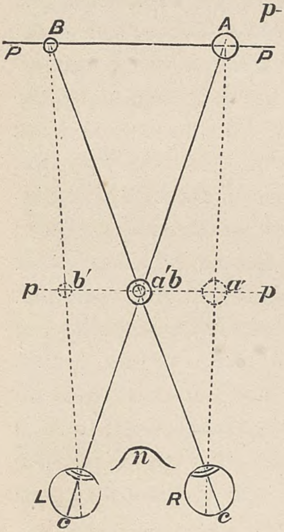
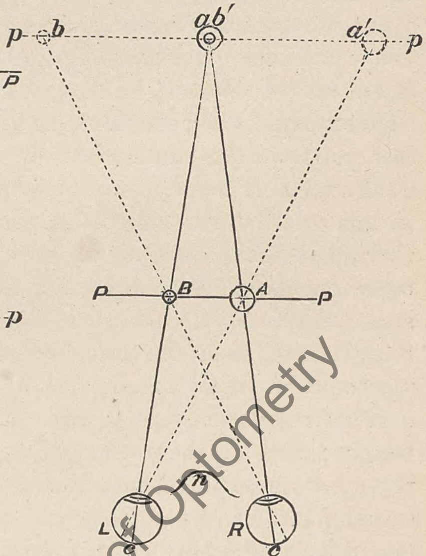



FIG. 43.




In both figures the letters are the same. *R* and *L*, the two eyes; *A* and *B*, two objects; *a′b*, Fig. 42, and *ab′*, Fig. 43, combined images; primed letters, left-eye images; *c c*, central spots of retinæ; *n*, the nose; *P P*, plane of objects; and *p p*, plane of sight.

In Fig. 42 the right eye, *R*, is directed toward the object *B*, and the left eye, *L*, toward the object *A*.* The retinal images of these, falling on the central spots *c c*, are superposed at the point of

* In these figures I give position but not *size* of the combined images. This will be smaller or larger than the real size in proportion as the combined image is nearer or farther off than the real object.

sight (where the lines of sight intersect) and seen as $a'b$, while two shadowy images, $a$ and $b'$, are seen to the right and left. Their position, if referred to the plane of sight, and as determined by the law of direction, is given by connecting the points $R$ $A$ and $L$ $B$. In Fig. 43 the right eye, $R$, is directed toward the object $A$, and the left eye, $L$, toward the object $B$. The point of sight is therefore beyond, at the meeting of the optic axes or lines of sight. There the combined images, $ab'$, will be seen, while two other uncombined images will be seen at points determined by the law of direction, represented by continuing the lines $R$ $B$ and $L$ $A$ to the plane of sight. It is evident that in this case the two objects $A$ and $B$ must not be farther apart than the optic centers (interocular space); otherwise the lines of sight will not meet in a point of sight, and therefore the two images will not combine. Simple inspection of the diagrams will explain the phenomena, if the reader will bear in mind that capitals represent objects and small letters external images; and further, that the primed small letters represent left-eye images, the strong lines $P$ $P$ the actual plane of the objects, and the dotted lines $p$ $p$ the plane of sight or of the images.

I have often amused myself by combining in this way the faces of my friends. It is easy thus to make a composite face like the composite photographs we so often see. But in this case the composite face is not steady; sometimes the one, sometimes the other face prevails.

Many persons will not at first succeed in making these experiments, on account of the difficulty which most persons experience in watching double images and controlling the movements of the eyes. To such we

would recommend the following method: Let the two objects set up before the eyes in the first experiment be other than parts of the body of the observer—for example, a card and a rod, or two rods. Then, while looking at the table on which the objects lie, hold up the forefinger—or better, a pencil—between the eyes and the objects. The pencil will of course be double. Now, by bringing the pencil nearer or carrying it farther, its double images will separate or close up. Bring the pencil into such a position that its double images shall exactly coincide with the centers of the two objects which you desire to combine. If you now look at the pencil, the ocular convergence will be exactly suitable for combining the objects.

In the cases thus far mentioned there is no illusion: the combined images do not produce the appearance of a single *real* object, as in the case of combined images of the same object producing single vision; because, in the first place, the two objects are *dissimilar*, and therefore the combination is not perfect; and, in the second place, the illusion is destroyed by the existence of the two other uncombined images. We next try—

2. **Similar Objects.**—If the two objects, the images of which we desire to combine, are exactly similar, then the combined image will be exactly like a natural object. For example:

*Experiment 1.*—Place two pieces of money of the same kind on the table, being careful that the stamped figures shall be the same and in the same position. Now, looking down upon them, combine as before. Not only will the outlines of the two pieces combine, but the stamped figures in the minutest details, so that the middle combined binocular image will have all the appearance of a real object. This is illustrated by

Figs. 44 and 45, in which the position of parts is reversed, because the eyes are supposed to be looking down. In Fig. 44 the two objects (coins), $A$ and $B$,

Fig. 44.

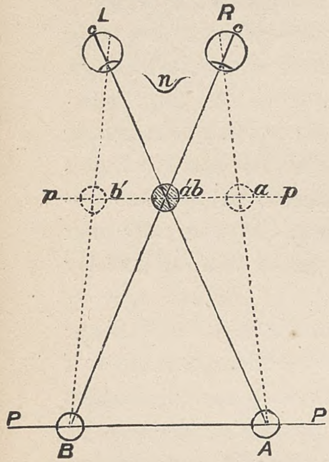
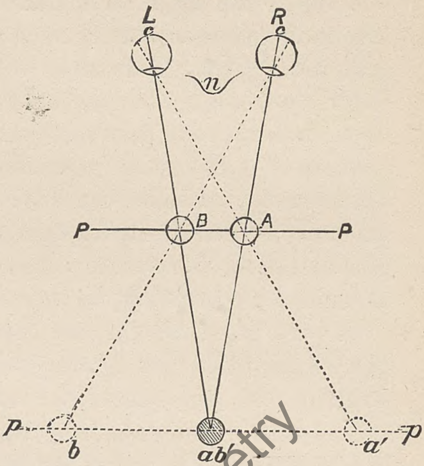



Fig. 45.

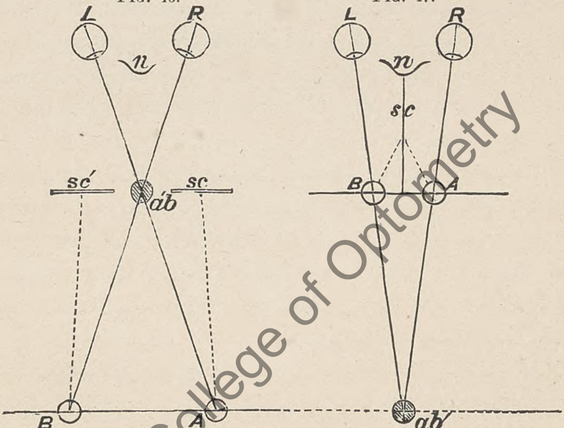



are combined by crossing the eyes, and the combined or binocular opaque image will be seen at the point of sight as $a'b$, while homonymous monocular shadowy images, $a$ and $b'$, will be seen right and left. In Fig. 45 the combination is made by looking beyond the plane of the coins, and the coins in this case must not be more than an interocular space apart. The combined images, like a real opaque object, will be seen at the point of sight $ab'$, and the two shadowy monocular images right and left, as before, only they are now heteronymous.

In this case, though the combination is perfect, yet the illusion is still not complete, because of the presence of the accompanying monocular images; but the formation of these may be prevented by the use of appropriate screens.

*Experiment 2.*—If in the first experiment with the money, before combining, we hold two cards, *sc*, *sc′*, Fig. 46, one in either hand and at about half the distance to the table (the best distance is the plane of combination or plane of sight, for then there will be no doubling of the cards), in such position that the card in the right hand, *sc*, will hide the right piece *A* from the right eye but not from the left, and the card in the left hand, *sc′*, will hide the left piece *B* from the left eye but not from the right, and then make the combination by crossing the eyes, the combined binocular opaque image will be formed as before; but the monocular images will not appear, because there will be no

Fig. 46. Fig. 47.




other retinal image formed except on the central spots. This is represented in Fig. 46. In case we combine beyond the plane of the objects, then a median screen, *sc*, Fig. 47, extending from the root of the nose *n* to the table, midway between the objects, will prevent the formation of the monocular images, as shown.

Or the same results may be obtained without the use of screens by causing the two monocular images to fall on the blind spots.

*Experiment 3.*—Place two similar small coins on the table 5 or 6 inches apart and combine as before by convergence. Now looking steadily at the combined image, move the head nearer or farther away. At a certain distance the monocular images disappear and only the one combined image remains, looking like a real coin lying on the table.

But in these cases, although the union of the two images is perfect, and although we see nothing but an apparently solid opaque object, even yet the illusion is not absolute; partly because the details of the table are doubled and therefore the table looks unreal, and partly because the eye is adjusted to the point of sight, whereas the light comes from the object, which is either nearer as in Fig. 47, or farther off as in Fig. 46, than that point.

This case may be varied in many ways. (*a*) Take a card and make in it two pin holes exactly an interocular space apart. Lay it on the face so that the two holes shall be before the two eyes. Each hole will be seen by its own eye alone, the other hole being hid by the nose. They will unite completely and only *one hole* will be seen in the middle, through which both eyes seem to look. (*b*) Spectacles when on the nose are a good illustration. There are two circles, one seen by each eye and hidden from the other eye by the nose. They therefore combine and we see but *one circle* in the middle through which we look with both eyes. (*c*) For those who are so fortunate as to have a friend with whom they can take such a liberty, we would recommend the following: Place the two faces

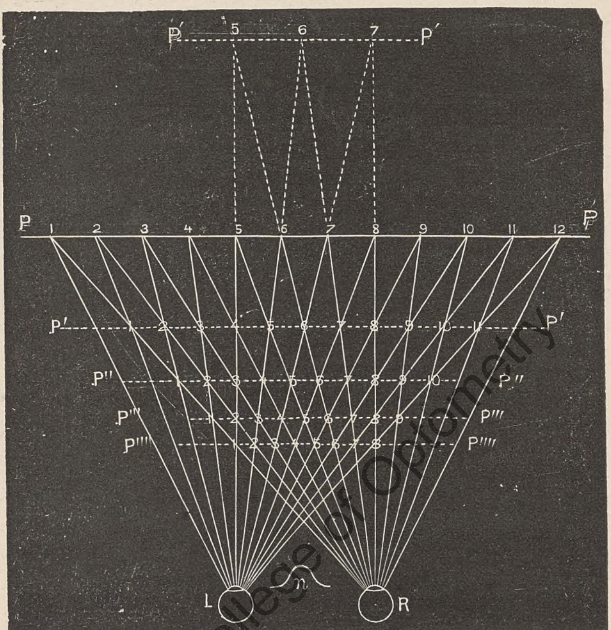
together, forehead to forehead, nose to nose, and gaze straight into the eyes. Only *one eye* will be seen in the middle. Those who are not so fortunate may make the same experiment on their own faces in a mirror.

But in all the preceding cases, for one reason or another, the illusion still lacks completeness. We will therefore try still another case.

3. **Many Similar Objects regularly arranged.**—The illusion is most complete when we combine the images of many similar objects regularly arranged over the whole field of view, such as the regular figures of a tessellated pavement or oilcloth, or of a regularly figured carpet of small pattern, or of a papered wall of regular pattern, or the diamond-shaped spaces of a wire grating. In such a case, when by convergence we combine two contiguous figures immediately in front, other contiguous figures all over the plane also combine, and we see a phantom as perfect as reality itself, but with the figures smaller than the real. In other words, by the motion of the eyes in opposite directions in convergence, the images of the whole plane of the figured surface are slidden by one eye to the left and by the other eye to the right, until combination takes place again over the whole field. When the combination is effected, if we hold the point of sight steady, the combined images of the figures, at first a little blurred, become sharp and clear; and then the whole figured plane comes forward to the point of sight, and appears there as distinctly as a real object, but on a smaller scale in proportion to the less distance. This is represented in Fig. 48, in which the strong line *P P* represents the plane of the regular figures 1, 2, 3, 4, 5, etc. When contiguous figures, 6 and 7, are united by convergence at the point of sight, and seen there, then

all other contiguous figures, 1 and 2, 2 and 3, etc., all over the plane, will be similarly united, and the whole plane with all its figures will advance and be distinctly seen at the distance $p' \; p'$. When by stronger convergence alternate figures, 5 and 7, are combined at a nearer point of sight 5 on the plane $p'' \; p''$ —or (which is the

Fig. 48.




same) when we use the plane $p' \; p'$ first obtained with all its figures as a real object, and again combine contiguous figures—the whole plane advances to $p'' \; p''$, and is seen as a distinct object with a *still smaller pattern* of figures. Using the plane thus obtained again as an object, and uniting its contiguous figures, the whole

plane again advances still nearer, and the figures become still smaller at $p''' \, p'''$. In this manner I have often distinctly seen a regularly figured wall or pavement on six or seven different planes coming nearer and nearer, and becoming smaller and smaller, until the nearest was within 3 inches of the eyes, and the figures in exquisite miniature, and yet the whole so apparently real that it seemed to me I could rap my knuckles against the wall or pavement. When thus looking at the nearest image, by a slight relaxation of convergence, we may drop the image and catch it on the next plane, and again drop it to each successive plane, until it falls to its natural place. In cases of extreme convergence, as in plane'''', the phantom plane is not flat, but convex. This will be explained hereafter—Chapter III, Part III.

If the figures of the pattern are not larger than the distance between the optic centers ($2\frac{1}{2}$ inches), then it is possible also to unite the figures beyond the real plane —i. e., on the plane $P' \, P'$. In this case the figures will be proportionately enlarged, as shown by the diagram. But it is difficult by this method to make the image clear, the reason for which we shall soon see.

In all cases of illusive images or phantoms the head ought to be held steady. If it be moved from side to side while gazing at such an image, the image will also move from side to side—in the same direction as the head if the point of sight be nearer than the object, and in the opposite direction if the point of sight be beyond the object—i. e., in both cases there is a parallactic turning about a point at the distance of the real object. It is necessary too, in all experiments on combination of images, that the interocular line should be exactly parallel with the line joining the objects to be

combined; otherwise one image will be higher than the other.

**Dissociation of Consensual Adjustments.**—We have said above that when the combination in case 3 (and so also in the other cases) is first obtained, the image of the figures is not distinct, but afterward becomes clear and sharp. The reason is this: The voluntary adjustment of the optic axes (axial adjustment) to a nearer distance than the object carries with it, by consensus, the focal adjustment and pupillary contraction for the same distance. But since the lenses are adjusted for a nearer distance than the object, the retinal image will be indistinct. The subsequent clearing of the image, therefore, is the result of a dissociation of the axial and focal adjustments. The optic axes are adjusted for the point of sight or distance of the illusive image or phantom, and the lenses are adjusted for the distance of the object. Some persons do not find it easy to make this dissociation, and therefore to make the illusive image perfectly clear. To presbyopic persons it is not difficult, but normal eyes will find some, though not insuperable, difficulty. All difficulty, however, may be removed by the use of glasses—concave in the case of combination by squinting, and convex in the case of combination beyond the plane of the object. But of course each pair of glasses can remedy the difficulty for *one* distance only.

Now it becomes an interesting question: When the axial and focal adjustments are thus dissociated, with which one does the pupillary contraction ally itself? I answer, it allies itself with the *focal* adjustment. This may be proved as follows:

*Experiment.*—While the combination and the formation of the illusive image are taking place, let an

assistant standing behind observe the pupil in a small mirror suitably placed in front and a little to one side of one eye. He will see that at first the pupil contracts strongly, associating itself with the axial and focal adjustments to the point of sight; but as soon as the illusive image clears and becomes distinct, he will observe that the pupil has enlarged again.*

**General Conclusions.**—It is evident, therefore, that the combination of the similar images of two different objects may produce the same visual effect as the combination of the two images of the same object. In other words, single vision, or ordinary perception of objects, is by combination of two similar images; and it makes no difference whether the two images belong to the same object or to two different but similar objects. This idea must be clearly apprehended and held fast; otherwise all that follows will be unintelligible.

Again, it is evident that two objects may be seen as one, and, contrariwise, one object may be seen as two images. We see then the absolute necessity, in binocular vision, that we should speak of seeing only *external images*, the *signs of objects*. They are usually—i. e., under ordinary conditions—the *true* signs, but often untrue, deceptive, illusory signs. Images the signs of objects! Does this seem strange? Do we not continually see images in mirrors; and do we not often mistake them for objects although they are only the *signs* of objects?

* I have reason to believe that this is not always the case. Prof. Le Conte Stevens, who is a very careful and competent experimenter in binocular phenomena, tells me that in his case the pupil allies itself with the ocular convergence, and therefore does not dilate when the phantom clears.

## CHAPTER III.

### *BINOCULAR PERSPECTIVE.*

Thus far we have investigated the case of *flat* objects, or of figures or colored spaces *on a plane.* We have shown how the images of these may be combined at pleasure, so as to give the illusory appearance of objects or figures at places and of sizes different from their real places and sizes. We come now to the more complex case of *solid objects of three dimensions*, and of objects situated at *different distances*. We have shown that we perceive relative position in *two* dimensions by the *law of direction.* But how is it with relative position in the *third* dimension? We now proceed to show that this is due to the *law of corresponding points.* This brings us to the important subject of the perception of depth of space so far as this is connected with binocularity; or, in other words, to the subject of *binocular perspective.* We will introduce the subject with some simple experiments.

*Experiment 1.*—Place one forefinger before the other in the median plane, as in experiment 3 on page 109. As already seen, when we look at the farther finger and see it single, the nearer one is doubled heteronymously; when we look at the nearer finger and see it single, the farther one is doubled homonymously. *We can not see them both single at the same time.* The reason is obvious. If we shut one eye, say the left, we

see the fingers as in Fig. 49, I; if we shut the right eye, we see them as in Fig. 49, II. Now these two can not be combined, because they are different. When we combine the images of the farther fingers, *a* and *a′*, the nearer, *b* and *b′*, will not have come together yet, and will therefore be heteronymously double, as in Fig. 50, I;

Fig. 49.

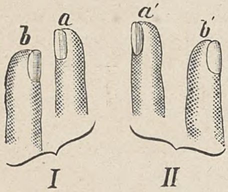
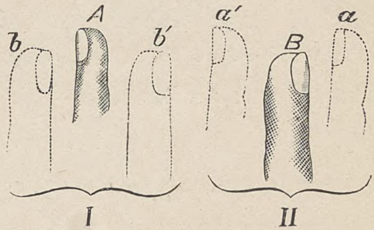



Fig. 50.



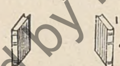

when by greater convergence we combine the images *b* and *b′* of the nearer finger, then the images *a* and *a′* of the farther will have crossed over and become homonymously double, as in Fig. 50, II. As in previous experiments, double images are given in dotted outline because transparent, and left-eye images are marked with primed letters, and combined images with capitals.

Now, in this experiment we are distinctly conscious of a *greater* convergence of the optic axes necessary to combine the double images of the nearer finger, and of a *less* convergence to combine the double images of the farther. Thus the eyes range back and forth by greater and less convergence, combining the double images of the one and the other by transferring the point of sight from one to the other; and thus we acquire a distinct perception of distance between the two. It is literally a rapid process of triangulation, the base-line being the interocular distance.

Thus far we have explained the perception of depth of space between *separate* objects lying one beyond the other. We now take the case of a *single* object occupying considerable depth of space in the line of sight.

*Experiment 2.*—We take a rod about a foot long, and hold it in the median plane a little below the horizontal plane passing through the eyes, so that we can see along its upper edge, the nearer end about six or eight inches from the eyes. If now, shutting the left eye, we observe the projection of the rod against the wall, it will be like this— ${}_{a}/^{b}$ —$a$ being the nearer and $b$ the farther end. If we shut the right eye and open the left, the projection will be like this—${}^{b'}\backslash_{a'}$. These lines are exactly like the retinal images formed by the rod in the right and left eyes respectively, except that these images are inverted. Or, to express it differently, these lines would make images on the right and left retinæ respectively exactly like those made by the rod; they are the facsimiles of the external images of the rod. If we now open both eyes and fix attention on the farther end, then the nearer end will be seen double heteronymously, and the projection will be thus— $\overset{B}{{}_{a}\wedge_{a'}}$. If, on the contrary, we look at the nearer end, then this of course will be single, but the farther end will now be double homonymously, and the projection will be thus— $\underset{A}{{}^{b'}\vee^{b}}$. If, finally, we look at the middle point, this point will of course be seen single, but both ends double, the one homonymously, the other heteronymously, and the projection will be thus—${}^{b'}_{a}\times^{b}_{a'}$. Or, to put it differently, the

external images of the rod belonging to the two eyes respectively are like these lines— $_{a}/^{b}$ and $^{b'}\backslash_{a'}$ : if these two be brought together so as to unite the farther ends $b$ $b'$, then by greater convergence the middle points, and then by still greater convergence the nearer ends $a$ $a'$, the three projections above given are obtained; but it is obviously impossible to unite all parts and see single the whole rod at once. Now, if we observe attentively, we find that in looking at the rod the eyes range back and forth by greater or less convergence, uniting successively the different parts, and thus acquire a distinct perception of the difference of distance or depth of space between the nearer and the farther end.

*Experiment 3.*—We take next a small thin book, and hold it as before six to eight inches distant in the median plane, a little below the horizontal plane of sight, so that the back and the upper edge are visible. If we shut the left eye, we see the back, the upper edge, and the whole right side, thus— . The retinal image formed in the right eye is exactly like this figure, except that it is inverted; this figure makes exactly the same retinal image as the book does in the right eye; it is the facsimile of the external image of the book for the right eye. If we shut the right eye and open the left, we see the back, the upper edge, and the whole left side, thus— . Now, if we open both eyes, we must and do see both these images. If we look beyond the book, the two images are wholly separated, thus— . If we look at the farther part, we bring these

two images together so as to unite the farther part and see it single, but the nearer part or back is double, thus— . If we look at the nearer part or back, then this is seen single, but the farther edge is now double, thus— .* But by no effort is it possible to see it single in all parts at the same time, because these dissimilar external images can not be wholly united. The eyes therefore range rapidly back and forth, successively uniting different parts by greater and less convergence, and thus acquire a distinct perception of distance between the back and front, and hence of depth of space.

The fact that two eyes are necessary for accurate estimate of distance may be illustrated by many familiar facts. (*a*) Using one eye only we can not dip a pen into an inkstand with the same accuracy and confidence as with both eyes open. (*b*) If we wish to draw the outlines of a complex object, like a chair or a table, we shut one eye, so as to destroy as much as possible the perception of depth of space and to project the object on a plane at right angles to the line of sight. (*c*) If two brass balls be hung by fine black threads invisible in a darkish room, one a foot or two beyond the other, the farther one a trifle larger than the nearer, and viewed nearly in a line and from such a distance that their angular diameters are equal: then, using one eye, they will seem to hang side by side, and it will be impossible to say which is the farther off; but as soon as we use both eyes the depth of space between is perceived at once.

* Of course in these figures the amount of doubling is exaggerated in order to make the principle clearer.

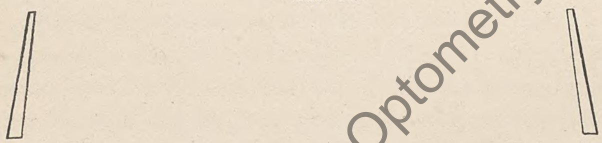
After these simple illustrations we are now prepared to generalize. It is evident that solid objects as seen by two eyes form different mathematical projections, and therefore form different retinal images in the two eyes, and therefore also different external images. Hence the images of the same object, whether retinal or external, formed by the two eyes, are necessarily dissimilar if the object occupies considerable depth of space. But dissimilar images can not be united wholly: for when by stronger convergence we unite the nearer parts, the farther will be double; and when by less convergence we unite the farther parts, the nearer will be double. Therefore the eyes run rapidly and unconsciously back and forth, uniting successively different parts, and thus acquire the perception of depth of space occupied by the object. But what is true of a single object is true of different objects placed one beyond the other, as the two fingers in experiment 1, page 138. We can not at the same time unite nearer and more distant objects, but the point of sight runs rapidly and unconsciously back and forth, uniting them successively, and thus we acquire a perception of depth of space lying between them. Therefore, *the perception of the third dimension*, viz., *depth or relative distance, whether in a single object or in a scene, is the result of the successive combination of the different parts of the two dissimilar images of the object or the scene:* dissimilar, because taken from different points, viz., the two eyes with the interocular distance between. This fundamental proposition will be slightly modified in our chapter on the theory of binocular perspective. In the mean time it must be clearly conceived and held fast; otherwise all that follows on stereoscopy will be unintelligible.

## THE PRINCIPLES OF STEREOSCOPY.

We have shown (pages 133–135) that we may have a phantom-*plane* where no plane exists. So also we may have a phantom-*space* where no space exists. Stereoscopy is the art of making such phantom-space.

We have already seen (page 112) that in binocular vision we see objects single by a combination of two similar or nearly similar images, and that therefore (page 137) it makes no difference whether the images are those of the same object or of different objects, if the images in the two cases are identical, and if we take care to cut off the monocular images which are formed in the latter case. Hence, if we draw two pictures of a rod in the two positions shown in Fig. 51, and then

Fig. 51.



combine them by converging the eyes, taking care to cut off the monocular images as directed on page 131, Fig. 46, the visual result will be exactly the same as that of an actual rod in the median line; and therefore it will look like such a rod. As in the case of the actual rod, by greater or less convergence of the optic axes we may combine successively different parts; and the eyes therefore seem to run back and forth, and we have a distinct perception of depth of space. To produce the proper effect, the two pictures of Fig. 51 ought to be combined at a distance of about one foot.

So also in the case of the book, page 141. If we exactly reverse the case described there—i. e., if we make two pictures of a book as seen by one eye and the other, and then combine them, cutting off the monocular images—we have the exact appearance of an actual solid book. The only reason why the illusion is not complete is, that there are other kinds of perspective besides the binocular; and in this case especially because there is not the same change of *focal adjustment* necessary for distinct image as in the case of a real object.

Now this is the principle of the stereoscope. The stereoscope is an instrument for facilitating the combination of two such pictures, and at the same time cutting off the uncombined monocular images which would tend to destroy the illusion.

**Stereoscopic Pictures.**—When we look at an object having considerable depth in space, or at a scene, there is an image of the object or scene formed on each retina. These two images are not exactly alike, because they are taken from different points of view. Now suppose we draw two pictures exactly like these two retinal images, except inverted. Obviously these two pictures will make images on the corresponding retinæ exactly like those made by the original object on the one retina and the other, and therefore will be exactly like this object seen by one eye and then by the other. Now, we have seen the wonderful similarity of the eye to a photographic camera. Suppose, then, instead of drawing the pictures like the two retinal images, we photograph them. Two cameras are placed before an object or a scene with a distance between of two or three feet. They are like two great eyes with large interocular space. The sensitive plate represents the retina, and

the pictures the retinal images. The photographic pictures thus taken can not be exactly alike, because taken from different points. *They will differ from each other exactly as the two retinal images of the same object or scene differ*, only certainly in a greater degree. Therefore, if these two photographs be binocularly combined as in the experiments previously given, they ought to and must produce a visual effect exactly like an actual object or scene; for in looking at an object or scene, we are only combining retinal images (or their external representatives) exactly like these pictures, because taken in the same way.

This is substantially the manner in which stereoscopic pictures are taken. It is not always necessary, indeed, to have two cameras; for the pictures, being permanent and not evanescent like retinal images, may be retained combined at any time. The object or scene is often photographed from one position, and then the camera is moved a little, and the same object or scene is again photographed from the new position. The two slightly dissimilar pictures thus taken are then mounted in such wise that the right-hand picture shall be that taken by the right camera, and the left-hand picture that taken by the left camera. In other words, they are mounted so that the right picture shall be similar (except inverted) to the retinal image of the object or scene in the right eye, and the left picture to the retinal image in the left eye. The marvelous distinctness of the perception of depth of space, and therefore the marvelous resemblance to an actual object or scene, produced by binocular combination of such pictures properly taken and properly mounted, is well known.

It is easy to test whether stereoscopic pictures are

properly mounted or not. Select some point or object in the foreground; measure accurately with a pair of dividers the distance between it and the same point or object in the other picture; compare this with the distance between identical points in the extreme background of the two pictures. The distance in the latter case ought to be greater than in the former. This is the proper mounting for viewing pictures in a stereoscope. If they are to be combined with the naked eye by convergence, then the reverse mounting is necessary.

**Combination of Stereoscopic Pictures.**—Stereoscopic pictures may be easily combined by the use of the stereoscope or with the naked eyes. For inexperienced persons, however, the latter is more difficult and the illusion less complete, unless with special precautions. Nevertheless, it will be best to begin with this method, because the principles involved are thus most easily explained.

**Combination with the Naked Eyes.**—(*a*) *Beyond the plane of the picture.* In combining stereoscopic pictures with the naked eyes, there are two difficulties in the way of obtaining the best results. First, it is evident that such pictures, as usually mounted, were intended to be combined *beyond the plane of the card;* for it is only thus that the object or scene can be seen in natural perspective, and of natural size, and at natural distance. But in thus combining, the eyes are of course looking at a distant object, and consequently parallel or nearly so. The eyes are therefore focally adjusted for a distant object, but the light comes from a very near object, viz., the card-pictures. Hence, although the pictures unite perfectly, the combined image or scene is indistinct. Myopic eyes will not experience this difficulty, and in normal eyes it may be remedied by the

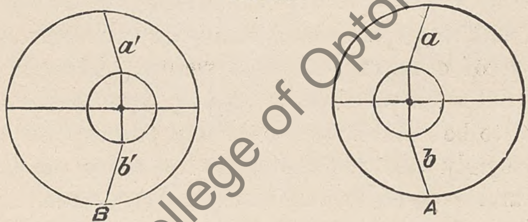
use of slightly convex glasses. Such glasses supplement the lenses of the eye, and make clear vision of a near object when the eyes are really looking far away; or, in other words, make a clear image of a near object on the retina of the *unadjusted* eye.

Another difficulty is, that the pictures are usually so mounted that identical points are farther apart than the interocular distance, and therefore, even with the optic axes parallel—i. e., looking at an infinite distance—the pictures do not combine. This difficulty is easily removed by cutting down the inner edges of the two pictures, in order to bring them a little nearer together, so that identical points in the background shall be equal to or a little less than the interocular distance.*

With this explanation we now proceed to give examples of naked-eye combination.

Fig. 52 represents a projection of a skeleton truncated cone made of wire, as seen from two positions a

FIG. 52.




little separated from each other; in other words, as they would be taken by two cameras for a stereoscopic card; or, again, as they would be taken on the retinæ of the two eyes looking at such a skeleton truncated cone with the smaller end toward the observer.

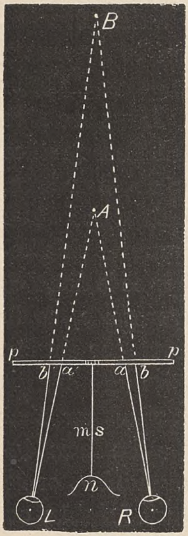
* In a subsequent chapter we give the method of determining with accuracy the interocular distance.

*Experiment.*—If we now place a median screen 10 inches or a foot long midway between these two figures, *A* and *B*, and place the nose and middle of forehead against the other edge of the screen, so that the right eye can only see *A* and the left eye *B*—assisting the eye with slightly convex glasses if necessary—and then gaze as it were at a distant object beyond the plane of the picture, the two figures will be seen to approach and finally to unite in one, and *appear as a real skeleton truncated cone* of a considerable height. If we are able to analyze our visual impressions, we shall find further that, when we look steadily at the larger circle or base, the smaller cone or summit is slightly double, and when we look steadily at the smaller circle or summit this becomes single, but now the larger circle or base is double; further, that it requires a greater convergence, as in looking at a nearer object, to unite the smaller circles, and a less convergence, as in looking at a more distant object, to unite the larger circles; and still further, that the lines $a\ a'$ and $b\ b'$ behave exactly like the lines described on page 140, forming a V, an inverted V, or an X, according to the distance of the point of sight; or, in other words, behave exactly like the two images of a rod held in the median plane with one end nearer than the other. In a single word, the phenomena are exactly those produced by looking at an actual skeleton cone made of wires. Thus, as in the case of an actual object, the eyes by greater or less convergence run their point of sight back and forth, uniting different parts, and thus acquire a distinct perception of depth of space between the smaller and larger circles.

The same is true of all pictures constructed on this principle, and all objects or scenes on stereoscopic cards. In these, it will be remembered, identical points in the

foreground are always nearer together than identical points in the background; therefore, when the background is united the foreground is double and *vice versa.* We may represent these facts diagrammatically by Fig. 53, in which *p p* is the plane of the pictures; *ms*, the median screen resting on the root of the nose, *n*; *R L*, the right and left eyes. On the plane of the picture *p p*, *a* and *a'* represent identical points in the foreground, viz., the centers of the small circles in the diagram Fig. 52; and *b* and *b'* identical points in the background (centers of the larger circles in Fig. 52). Now when the eyes are directed toward *b* and *b'*, the two visual lines will pass through these points, and the images of these two points will fall on corresponding points of the retinæ, viz., on the central spots, and will be united and seen single. But where? Manifestly at the point of optic convergence or point of sight *B*. Now when *b* and *b'* fall on corresponding points and are seen single, evidently *a* and *a'* must fall on non-corresponding points, viz., the two temporal portions of the retinæ, and are therefore seen double heteronymously. When, on the other hand, by greater convergence the optic axes are turned on *a* and *a'*, then the images of these fall on the central spots, and are seen single at the nearer point of sight *A*; but now *b* and *b'* are seen double homonymously, because they fall on non-corresponding points, viz., the two nasal halves of the retinæ. Intermediate points be-

FIG. 53.



tween the background and foreground will be seen at intermediate points between $B$ and $A$. Thus the point of sight runs back and forth from background $B$ to foreground $A$, and we acquire a distinct perception of depth of space between these two points.

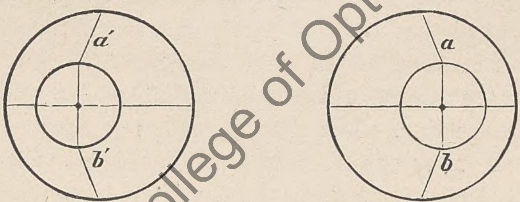
(*b*) *Combination on this side the picture.* But, for those at all practiced in binocular experiments, by far the most perfect naked-eye combination is obtained by crossing the eyes, i. e., by combining on the *nearer* instead of the farther side of the pictures. For this purpose, however, it is necessary that the mounting be reversed; i. e., the right-hand picture must be put on the left side, and the left-hand picture on the right side of the card. By this reversal it is evident that identical points in the background of the two pictures are nearer together than identical points in the foreground.

If, now, holding such a card before us at any convenient distance, say 18 inches or 2 feet, we converge the optic axes so that the right eye shall look across directly toward the left picture, and the left eye toward the right picture, then the two pictures will unite at the point of crossing of the optic axes (point of sight), and will be seen there in exquisite miniature, but with perfect perspective. The effect is really marvelously beautiful. For persons of slightly presbyopic eyes there will be no difficulty in getting the combined image perfectly clear. In normal eyes, as already explained (page 135), there must be dissociation between the axial and focal adjustments before the combined image is perfectly clear. For those who can not make this dissociation it may be necessary to use very slightly concave glasses. Again, if the observer is annoyed by the existence of the monocular uncombined images to the right and

left, it will be best to use two side screens, as already explained (page 131), instead of the median screen used in combining beyond the plane of the picture.

*Experiment.*—I draw (Fig. 54) two projections of a skeleton truncated cone precisely like those represented on page 148, but reversed. It is seen, for example, that the centers of the small circles are in this case farther apart than the centers of the large circles. If, now, holding these about 18 inches distant, I combine them by crossing the optic axes, the impression of a skeleton truncated cone with the smaller end toward me is as complete as possible. The singleness of the impression at first seems perfect, but by observing attentively the lines $a$ and $a'$ it will be seen that they unite only in points and not throughout—that they come together as a v, thus—V, or an inverted v—Λ, or an x—X, according to the distance of the point of sight. In other words, when by greater convergence the small circle is single, the larger circle is double; and when by less conver-

FIG. 54.

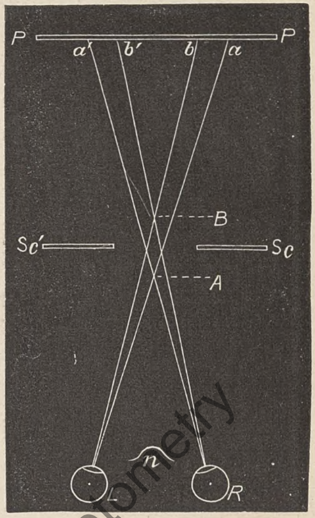



gence the larger circle is single, then the smaller circle is double. And thus the eyes run the point of sight back and forth, uniting first the one and then the other, and in this way acquire a clear conception of depth of space between the smaller and larger circles. If, while the figures are combined, the page be brought nearer or

carried farther away, the cone shortens or lengthens proportionately.

These facts are illustrated by the diagram Fig. 55, in which, as before, $R$ and $L$ are the two eyes; $n$, the root of nose; $PP$, the plane of the pictures; $a$ and $a'$, identical points of the foreground, and $b$ and $b'$ of the background; and $sc$ and $sc'$, the two side-screens to cut off monocular images. When the eyes are directed toward $a$ and $a'$, these unite and are seen at the point of sight as a single object $A$, but $b$ $b'$ are double. When the eyes by less convergence are directed to $b$ and $b'$, then these are seen single at the point of sight $B$, but $a$ $a'$ are double. The point of sight runs back and forth from $A$ to $B$, and we thus acquire distinct perception of depth of space between.

FIG. 55.




Of course, any stereoscopic pictures may be combined in this way if we reverse the mounting; and I am quite sure that any one who will try it will be delighted with the beautiful miniature effect and the perfection of the perspective.

**Combination by the Use of the Stereoscope.**—The stereoscope is an instrument for facilitating binocular combinations beyond the plane of the pictures. By means of lenses also it supplements the lenses of the eyes, and thus makes on the retinæ perfect images of a near ob-

ject, although the eyes are looking at a distant object, and are therefore unadjusted for a near one. The lenses also enlarge the images, acting like a perspective glass, and thus complete the illusion of a natural scene or object.

It is difficult to convince many persons that there is in the stereoscope any doubling of points in the foreground when the background is regarded, and *vice versa*. But such is really always the fact; and if we do not observe it, it is because we have not carefully analyzed our visual impressions. It is best observed in skeleton diagrams of geometrical figures, such as are commonly used to explain the principles of stereoscopy. In ordinary stereoscopic pictures it is also easily observed in those cases where points in the extreme foreground and background are in the same range; as, for example, when a column far in front is projected against a building. In such a case, when we look at the building the column is distinctly double, and *vice versa*. For myself, I never look at a stereoscopic card, whether in a stereoscope or by naked-eye combination, without distinctly observing this doubling. For example: I now combine in a stereoscope the stereoscopic pictures of a skeleton polyhedron. The illusion of a polyhedral space inclosed by white lines is perfect. Now, when I look at the farther inclosing lines I see the nearer ones double, and *vice versa*. Moreover, I perceive that this doubling is absolutely necessary to the stereoscopic effect, for it is exactly like what would take place if I were looking at an actual skeleton polyhedron.

**Inverse Perspective.**—*Pseudoscopy.*—I have heard a few persons declare that they saw no superiority of a stereoscope over an ordinary enlarging or perspective glass; that they saw just as well while looking through

the stereoscope if they shut one eye as with both eyes open. Such persons evidently do not combine prop-

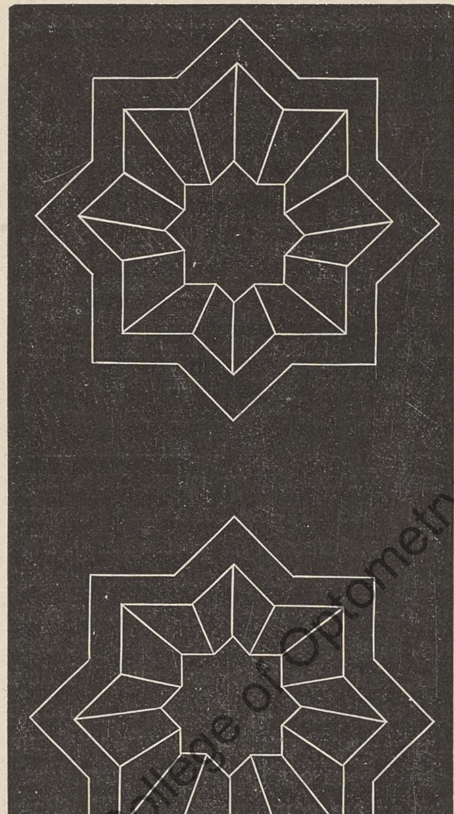


FIG. 56.

erly the two pictures, and they lose a real enjoyment. That the binocular is a real perspective, entirely differ-

ent from other kinds, may be clearly demonstrated by the phenomena of inverse perspective now about to be described.

If stereoscopic diagrams suitably mounted for viewing in a stereoscope be combined with the naked eye by squinting (crossing the optic axes), as in Fig. 55 (page 153), or if such diagrams properly mounted for combination by squinting be viewed in the stereoscope, the perspective is completely reversed, the background becoming the foreground, and *vice versa.* For example, Fig. 56 represents a stereoscopic card. When the two pictures are combined with a stereoscope the result is a jelly-mold with the small end toward the observer; but if the same be combined with the naked eye by squinting, we have now beautifully shown the same jelly-mold reversed, and we are looking into the hollow. If there should be other forms of perspective strongly marked in the pictures, these may even be overborne by the inverse binocular perspective. For example, in the stereoscopic picture Fig. 57, representing the interior of a bridgeway, the diminishing size of the arches and the converging lines, even without the stereoscope, at once by mathematical perspective suggest the interior of a long archway. This impression is greatly strengthened by viewing it in the stereoscope; for the binocular perspective and the mathematical perspective strengthen each other, and the illusion is complete. But if we combine these with the naked eyes by squinting, we see with perfect distinctness, not a *long* hollow archway, the small arch representing the *farther end*, but a *short* conical solid, with the small end *toward the observer.* Thus the binocular perspective entirely overbears the mathematical.

The cause of this reversal of the natural perspective

is shown in the following diagrams. In Fig. 58 the mounting is reversed, as seen by the fact that the points

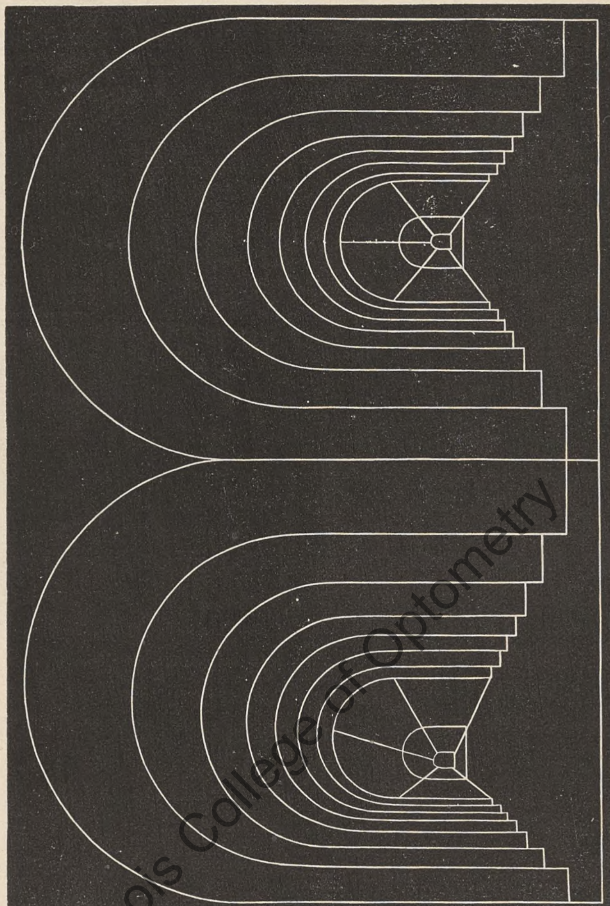


Fig. 57.

*b* and *b'* in the background are nearer together than the points *a* and *a'* in the foreground. By combining these in a stereoscope, the background is seen nearer the ob-

server at $B$, and the foreground thrown farther back to $A$. In Fig. 59 the pictures are mounted suitably for viewing in the stereoscope, but are combined by the naked eye. Here also the perspective is reversed,

Fig. 58.

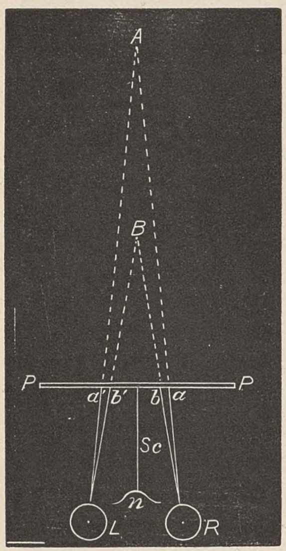
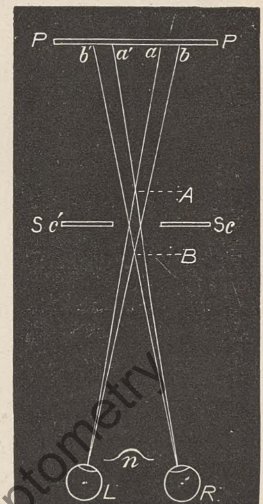



Fig. 59.



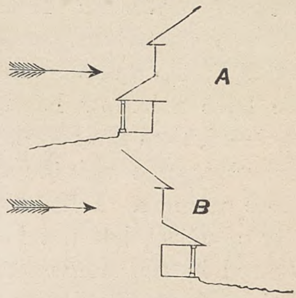

Inverse Perspective.

for the background is seen at a nearer point $B$, and the foreground at a farther point $A$.

This inverse perspective is easily brought out, not only in stereoscopic diagrams, but in nearly all stereoscopic pictures, even in those representing extensive and complex views. In these, of course, when viewed in the stereoscope, the binocular is in harmony with other forms of perspective, and each enhances the effect of the other. But if we combine with the naked eyes by squinting, or if we reverse the mounting and view again

with the stereoscope, there is in either case a complete discordance between the binocular and other forms of perspective. In some cases the ordinary perspective is too strong for the binocular, and the only result is a kind of confusion of the view; but in others the binocular completely overbears all opposition and reverses the perspective, often producing the strangest effects. For example, I now take up a stereoscopic card representing a building with extensive grounds in front. I view it in a stereoscope. The natural perspective comes out beautifully—the fine building in the background, the sloping lawn in the middle, and a piece of statuary and a fountain in the foreground. I now combine the same with the naked eyes by squinting. As soon as the combination is perfect and the vision distinct, the house is seen in front, and through a space in the wall the statue and fountain are seen behind. Observing more closely, all the parts of the house, the slope of the roof, and the slope of the lawn are also reversed. In Fig. 60, $A$ and $B$ show the natural and the inverted perspective in section, and the arrows the direction in which the observer is looking. In the one case the roof and the lawn slope downward and toward the observer; in the other, downward and away from the observer. In the one case the building is a solid object; in the other it is an inverted shell, and we are looking at the interior of the shell.

FIG. 60.




In nearly all stereoscope views I can thus invert the perspective by naked-eye combination. Almost

the only exceptions are views looking up the streets of cities. Here the mathematical perspective is too strong to be overborne. Stereoscopic pictures of the full moon are quite common.* If these be viewed in a stereoscope, we have the natural perspective, viz., the appearance of a globe; if combined with the naked eyes by squinting, we have a hollow hemisphere. If the mounting be reversed, then the hollow is seen in the stereoscope and the solid globe with the naked eyes. We will give one more example. I have now a stereoscopic view of the city of Paris, but not looking up the streets. When viewed in the stereoscope, the perspective is natural and perfect; the large houses are in the foreground and below, and the others gradually smaller and higher, until the dimmest and smallest are on the uppermost part and form the distant background. I am looking on the *upper surface* of a receding *rising* plane full of houses. I now combine the same pictures with the naked eyes by squinting. As soon as the combined image comes out clear, I see the smallest and dimmest houses on the upper part of the scene, but nearest to me. I am looking on the *under side* of a receding *declining* plane, on which the houses grow larger and larger in the distance, until they become largest at the lowest and farthest margin of the plane. If the mounting of the pictures be reversed, then the natural perspective will be seen with the naked eyes, and the inverse perspective just described will be seen in the stereoscope.

The extreme accuracy of our judgment of relative

* These may be made either by simultaneous photographs taken at widely different longitudes on the earth's surface, or else by taking two photographs at times of extreme libration of the moon to one side and the other.

distance by binocular perspective is well shown by the combination, either by the naked eyes or by the stereoscope, of apparently identical figures on a flat plane (as in Fig. 48, page 134). For example, in combining with the naked eyes the figures of a regularly figured wall-paper or tessellated pavement, the least want of perfect regularity in the size or position of the figures is at once detected by an appearance of gentle undulations or more abrupt changes of level. This fact is made use of in detecting counterfeit notes. If two notes from the same plate be put into a stereoscope and identical figures combined, the combination is absolute and the plane of the combined images is perfectly flat; but if the notes be not from the same plate, but copied, slight variations are unavoidable, and such variations will show themselves in a gently wavy surface.

*Monocular Pseudoscopy.*—There *is*, indeed, a *monocular* pseudoscopy too; for, as will be presently shown, there are other modes of judging of relative distance (perspective) besides the binocular. Thus, for example, photographs of moon craters, or actual wood carvings and moldings, are often seen *in reverse of their real relief*. But in all such cases the direction of relief is uncertain and often reversible at will by the imagination, like the faces of geometric diagrams of solids. But binocular pseudoscopy is not thus reversible. It has all the "sober certainty" of reality.

**Different Forms of Perspective.**—In order to bring out in stronger relief the distinctive character of binocular perspective, it is necessary to mention briefly the several different forms of perspective. There are many ways in which we judge of the relative distance of objects in the field of view, all of which may be called modes of perspective.

1. *Aërial Perspective.*—The atmosphere is neither perfectly transparent nor perfectly colorless. More and more distant objects, being seen through greater and greater depths of this medium, become therefore dimmer and dimmer and bluer and bluer. We judge of distance in this way; and if the air be more than usually clear or more than usually obscure, we may misjudge.

2. *Mathematical Perspective.* — Objects become smaller and smaller in appearance, and nearer and nearer together, the farther away they are. Thus streets appear narrower and narrower, and the houses lower and lower, with distance. Parallel lines of all kinds, such as railway stringers, bridge timbers, etc., converge more and more to a vanishing point.

3. *Monocular or Focal Perspective.*—Objects at the distance of the point of sight are distinct, the lenses being focally adjusted for that distance; but all objects beyond or within this distance are dim. Now, we are aware of a greater or less effort of adjustment to make a distinct image, according to the nearness or the distance of the object looked at. This is also a means of judging of the distance especially of near objects.

These three forms may all be called *monocular;* for they would equally exist, and we could judge of distance, so far as these modes are concerned, equally well, if we had but one eye. But there is still another, viz.:

4. *Binocular Perspective.*—In order to combine the images of objects near at hand, we converge the optic axes strongly; for more distant objects, less and less according to their distance. By this constant change of axial adjustment necessary for single vision, the point of optic convergence is run rapidly back and forth; and thus, by a kind of rapid and almost unconscious trian-

gulation, we estimate the relative distance of objects in the field of view. The man with only one eye can not judge by this method, and thus often misjudges the distance of near objects. In rapidly dipping a pen into an inkstand, or putting a stopper into a decanter, the one-eyed man can not judge so accurately as the two-eyed man. If we shut one eye and attempt to plunge the finger rapidly into the open mouth of a bottle, we are very apt to overreach or fall short.

As clearness of vision is confined to a small area about the point of sight, and rapidly fades away with increasing distance in any direction on the same plane, so clearness and singleness of vision are confined to the distance of the point of sight, and images become dim and double in passing beyond or to this side of that point. Again, as we sweep the point of sight about laterally over a *wide* field of view, and gather up all the distinct impressions into one mental image, so we run the point of optic convergence back and forth, gauging space, and gather up a mental picture of the relative distance of objects, in a *deep* field.

These different forms of perspective operate for very different distances. The focal adjustment becomes imperceptible for distances greater than about 20 feet. Judgments based on this, therefore, are limited within that distance. Binocular perspective operates perceptibly for much greater distance, perhaps a quarter of a mile; but beyond this it becomes imperceptible. The other two forms, the mathematical and aërial, operate without limit. Thus at near distance all forms of perspective coöperate. But as we go farther away first focal perspective drops out at about 20 feet; then binocular perspective at about a quarter of a mile; the other two remaining indefinitely.

Now the painter can imitate the aërial perspective. He skillfully diminishes the brightness, dulls the sharpness of outline, and blues the tinge of all objects, in proportion to their supposed distance, so as to produce the effect of depth of air. He can also and still more perfectly imitate the mathematical perspective, by diminishing the size of objects and the distance between them as he passes from his foreground to his background. But he can not imitate the focal perspective, and still less can he imitate the binocular perspective. This is artificially given only in the stereoscope, and is the glory of this little instrument. Focal perspective is unimportant to the painter, because imperceptible at the distance at which pictures are usually viewed; but the want of binocular perspective in painting interferes seriously with the completeness of the illusion. Therefore the illusion is more complete and the perspective comes out more distinctly when we look with only one eye. In a natural scene it is exactly the opposite: the perspective is far more perfect with both eyes open, because then all the forms coöperate.

---

**Return to the Comparison of the Eye and the Camera.** —It is time now to return to, and to continue, our comparison of the eye and the photographic camera. We have seen that both the camera and the eye are equally optical instruments contrived for the purpose of making an image; but we have also seen that in both this image is only a means by which to attain a higher end, viz., to make a photographic picture in the one case, and to accomplish distinct vision in the other. In both also, in order to accomplish its higher purpose, there must

be a sensitive receiving plate, viz., the iodized silver plate in the one, and the living retina in the other. In both, finally, there are wonderful changes, chemical or molecular or both, in the sensitive plate. Let us then continue the comparison.

1. In the photographic camera when accomplishing its work there are *three* images which may be mentally separated and described. First, the *light-image*. This is what we see on the ground-glass plate. It comes and goes with the object in front. It is the facsimile in form and color of the object, but diminished in size and inverted in position. Second, the *invisible image*. When the ground-glass plate is withdrawn and the sensitive plate substituted, the light-image falling on this plate determines in it wonderful molecular changes, which are graduated in intensity exactly according to the intensity and kind of light in the light-image: the aggregate effect is therefore rightly called an image, though it is invisible. Third, the *visible image*, or *picture*. The operator then takes the plate with the invisible image to a dark room, and applies certain chemicals which *develop* the image—i. e., which determine certain permanent chemical changes, which in intensity and kind are exactly proportioned to the antecedent molecular changes, and therefore graduated over the surface exactly as the molecular changes of the invisible image were graduated, and hence also exactly as the light of the light-image was graduated. This is the permanent photographic picture—the facsimile in form of the object which produced it.

So also in the work of the eye, vision, we may mentally separate and may describe three corresponding images. First, there is the *light-image*, which is formed in the dead as well as the living eye, and which comes

and goes with the object. Second, the *invisible image.* The light-image, falling on the sensitive living retina, determines in its substance molecular changes which are graduated in intensity and kind exactly as the light of the light-image is graduated in intensity and color, and may therefore be rightly called an image, even though it be invisible, and the nature of the molecular changes be inscrutable. Third, the *external visible image.* The invisible image, or the molecular changes which constitute it, is transmitted to the brain, and by the brain or the mind is projected outward into space, and hangs there as a visible external image, the sign and facsimile in form and color of the object which produced it.

2. Again, there are certain effects which can not be produced by one camera or by one eye. As two cameras from two positions take two slightly different pictures of the same object or the same scene, which when combined in the stereoscope produce the clear perception of depth of space—but only *phantom* space—even so the two eyes act as a double camera in taking and a stereoscope in combining two slightly different images of every object or scene, so as to give a clear perception of a *real* space.

We have thus carried the comparison as far as comparison is possible. But there is this essential difference between the two—essential because found everywhere between human and natural mechanism: In the one case we trace mechanism and physics and chemistry throughout. In the other we also trace mechanism, exquisite mechanism, but only to a certain point, beyond which we discover something higher than mere mechanism. We trace physics and chemistry to a certain point, but as we pursue the investigation we find

something superphysical and superchemical, or else a physics and a chemistry far higher than any we yet know. At a certain point molecular and chemical change is replaced by *sensation*, *perception*, *judgment*, *thought*, *emotion*. We pass suddenly into another and wholly different world, where reigns an entirely different order of phenomena. The connection between these two orders of phenomena, the material and the mental, although it is right here in the phenomena of the senses, and although we bring to bear upon it the microscopic eye of science, is absolutely incomprehensible, and must in the very nature of things always remain so. Certain vibrations of the molecules of the brain, certain oxidations, with the formation of carbonic acid, water, and urea, on the one side, and there appear on the other sensations, consciousness, thoughts, desires, volitions. There are, as it were, two sheets of blotting paper pasted together; the one is the brain, the other is the mind. Certain ink-scratches and ink-blotchings, *utterly meaningless*, on the one, soak through and appear on the other as *intelligible writing*. But how or why we know not, and can never hope even to guess. Certain physical phenomena—molecular vibrations, decompositions, and recompositions—occur, and there emerge, how we know not, psychical phenomena—thoughts, emotions, etc. Aladdin's lamp is rubbed—physical phenomenon—and the genie appears—psychical phenomenon.

# CHAPTER IV.

## *THEORIES OF BINOCULAR PERSPECTIVE.*

**Wheatstone's Theory.**—To Wheatstone is due the credit of having discovered the fact that two slightly dissimilar pictures—dissimilar in the same way as the two retinal images of a solid object or of a scene—when united, produce a visual effect similar to that produced by an actual solid object or an actual scene. He also invented the stereoscope to facilitate the combination of such pictures. His theory of these effects was as follows: In viewing a solid object or a scene, two slightly dissimilar images are formed in the two eyes, as already explained; but the mind completely unites or *fuses them into one.* Whenever there occurs such complete mental fusion of images really dissimilar in this particular way, and therefore incapable of mathematical coincidence, the result is a perception of depth of space, or solidity, or relief. In the stereoscope, therefore, he supposes that the two slightly dissimilar pictures are mentally fused into one, and hence the appearance of depth of space follows as the necessary result of this mental fusion.

This theory is still widely held by physiologists; but it is evidently the result of imperfect analysis of visual impressions. In stereoscopic *diagrams* it is always possible to detect the doubling on which the per-

ception of depth of space is based. It is a little more difficult in ordinary sterescopic *pictures*, and in natural scenes; but practice and close observation will always detect it in these also. It is most difficult of all to detect it in the case of single *solid objects;* but this is mainly because the doubling of the edges of such objects is usually out of the line of sight. Even where we can not detect the doubling, and yet binocularly perceive depth of space, such perception must be regarded as an example of unconscious cerebration. We actually ground our judgments upon impressions which do not emerge into clear consciousness.

Observe the degrees of this unconsciousness. Even the doubling of the forefinger, when held up before the eyes while we gaze at the wall, is undetected by some persons. To such the binocular perspective here seems to be a simple primary sense-perception. But the slightest scientific observation is sufficient to separate this apparently simple impression into its component elements, and thus to show that it is a judgment based on simpler elements. Next, the doubling of objects in the foreground of a scene or stereoscopic picture, when the background is regarded, fails to appear in consciousness. But analysis again shows that the perception of depth here also is not simple, but decomposable into simpler elements. Close observation again detects the elements on which judgment is based. Therefore, where we can not detect the simpler elements, we must believe that they still exist and that judgments are based upon them. Nothing can be more certain than that complete fusion never takes place; and if it seems so to us, it is only because we do not observe and analyze with sufficient care.

Wheatstone's theory therefore seems true only to

the unpracticed and unobservant. It makes that simple and primary which is capable of analysis into simpler elements. It is therefore a popular, not a scientific theory. It cuts, but does not loose, the Gordian knot.

**Brücke's Theory.**—Brücke and Brewster and Prévost, by more refined observation and more careful analysis, easily perceived that there was in reality no mental fusion of two dissimilar images. Their view, most completely expressed by Brücke,* is that which has been assumed in the foregoing account and explanation of binocular phenomena. It is, that in regarding a solid object or a natural scene, or two stereoscopic pictures in a stereoscope, the eyes are in incessant unconscious motion, and the observer, by alternately greater and less convergence of the axes, combines successively the different parts of the two pictures as seen by the two eyes, and thus by running the point of sight back and forth reaches by *trial* a distinct perception of binocular perspective or binocular relief, or depth of space between foreground and background.

That double images are really necessary to binocular perspective, as maintained by Brücke, is abundantly proved by the experiments already given on that subject. But one additional experiment may be given here to complete the proof.

*Experiment.*—As I look out of my window, I see the clothes-lines of a neighboring family, about 40 feet distant. Two of these are parallel, but one about 5 or 6 feet beyond the other. The lines being *horizontal*, no double images are visible when the head is erect. In this position I am unable to tell which line is the farther off. But when I turn the head to one side, so that the interocular line is at right angles to the cords,

* "Archives des Sciences," tome iii, p. 142 (1858).

immediately their relative distance comes out with great distinctness.

This theory is a great advance on the preceding. It is really a scientific theory, since it is based on an analysis of our visual judgments. It is also in part a true theory, and for this reason, in anticipation of what we believe to be a more perfect theory, we have used it in the explanation of many visual phenomena in the preceding pages. But it is evidently not the whole truth, as we now proceed to show.

1. If we place one object before another in the median plane of sight, even when we look steadily and without change of optic convergence at the one or the other, we distinctly perceive the depth of space between them. Evidently no *trial* combination, no running of the point of sight back and forth, and successive union and disunion of the images, are necessary for the perception of binocular relief. But if it be said that change of optic convergence does indeed take place, only rapidly and unconsciously, I proceed to prove that such is not the case.

2. *Dove's Experiment.*—The instantaneous perception of binocular relief is demonstrated by the now celebrated experiment of Dove. If a natural object, or a scene, or two stereoscopic pictures, be viewed by the light of an electric spark or a succession of electric sparks, the perspective is perfect, even though the duration of such a spark is only $\frac{1}{24000}$ of a second of time. On a dark night the relative distance of objects is perfectly perceived by the light of a flash of lightning, which according to Arago lasts only $\frac{1}{1000}$,* and according to Rood $\frac{1}{500}$† of a second. It is inconceiva

* Arago, "Œuvres Complètes," tome iv, p. 70.

† Rood, "American Journal of Science and Arts," vol. i, 1870, p. 15.

ble that there should be any change of optic convergence, any running of the point of sight back and forth, in the space of $\frac{1}{24000}$ part of a second. Evidently, therefore, binocular perspective may be perceived without such change of convergence. This point is certainly one of capital importance. The instantaneous perception of relief is fatal to Brücke's theory in its pure unmodified form. I have therefore repeated Dove's experiment with care, varying it in every possibly way, so as to guard against every source of error. These experiments completely confirm Dove's result, and establish beyond doubt the instantaneous perception of binocular relief. From a large number of experiments I select a few of the most conclusive and most easily repeated. The spark apparatus used was a Ritchie's Ruhmkorff capable of producing sparks 12 inches long. A Leyden jar was introduced into the circuit to increase the brilliancy of the sparks.

*Experiment 1.*—I select stereoscopic pictures in which other forms of perspective are wanting, or nearly so; skeleton geometric diagrams are the best. Standing in a perfectly dark room, and viewing these in a stereoscope by the light of a succession of sparks, the perspective is perfectly distinct with two eyes, but not at all with one eye.

*Experiment 2.*—I select a stereoscopic card like the last, except that mathematical perspective is also strong —such, for example, as a view of the interior of a bridgeway. Of course, as in the last case, the natural perspective is instantly perceived in the stereoscope; but this might be attributed to the mathematical perspective. But now hold the card in the hand and unite the pictures with the naked eyes by squinting, using again the spark-light: the inverse perspective described on page 157

will be brought out with perfect clearness with two eyes, but the natural perspective (mathematical) returns when we shut one eye. This experiment is conclusive, being removed from even the suspicion of the effect being the result of other forms of perspective; for in this case the binocular is opposed to all other forms of perspective, overbears them, and reverses the perspective.

So much for combination of stereoscopic pictures, whether beyond the plane of the card, as in the stereoscope, or on this side the plane of the card, as in naked-eye combination by squinting. We will next try the viewing of natural objects, eliminating as before as much as possible other forms of perspective.

*Experiment 3.*—Let two objects, as two brass balls, of the same size, be hung by invisible threads, one about 5 or 6 feet distant, and the other about 1 foot farther. At this distance focal adjustment is practically the same for the two balls, and thus this mode of judging of relative distance is eliminated. Let the balls be placed in the median plane of sight, or nearly so, in such wise that their relative distance may be easily detected with two eyes, but not with one. In the latter case—i. e., with one eye—they look like two balls side by side, the one a trifle larger than the other. Now, after darkening the room, try the experiment by the instantaneous flash of electric sparks. It will be found that under these conditions also the relative distance is perceived with perfect clearness with two eyes, but not with one.

It is certain, then, that binocular perspective is perceived instantly, and therefore without the *trial* combinations of different parts of the two images, as maintained by Brücke, Brewster, and others.

Between the two rival theories, therefore, the case stands thus: Wheatstone is right in so far as he asserts

immediate or instantaneous perception of relief, but wrong in supposing that there is a complete mental fusion of the two images. Brücke is right in asserting that binocular perspective is a judgment based on the perception of double images, but wrong in supposing change of optic convergence and successive trial combinations of different parts of the two images to be a necessary part of the evidence on which judgment is based.

**My own View** is an attempt to bring together and reconcile what is true in both of the preceding views. This, which I conceive to be the only true and complete theory, is hinted at, but not distinctly formulated, by Helmholtz.* I have strongly insisted upon it in all my papers on this subject. I quote from one of them: † "All objects or points of objects, either beyond or nearer than the point of sight, are doubled, but *differently*—the former homonymously, the latter heteronymously. The double images in the former case are united by *less* convergence, in the latter case by *greater* convergence, of the optic axes. Now, the observer knows *instinctively and without trial*, in any case of double images, whether they will be united by greater or less optic convergence, and therefore never makes a mistake, or attempts to unite by making a wrong movement of the optic axes. In other words, *the eye* (*or the mind*) *instinctively distinguishes homonymous from heteronymous images, referring the former to objects beyond, and the latter to objects this side of, the point of sight.*" Or again: In case of double images, "each eye, as it were, knows its own image," although such knowledge does not emerge into distinct consciousness.

* "Optique Physiologique," p. 939 *et seq.*

† "American Journal of Science and Arts," vol. ii, 1871, p. 425.

Thus, then, I conclude that the mind perceives relief *instantly*, but not *immediately;* for it does so *by means of double images*, as just explained. This is all that is absolutely necessary for the perception of relief; but it is probable—nay, it is certain—that the relief is made clearer by a ranging of the point of sight back and forth, and a successive combination of the different parts of the object or scene or pictures, as maintained by Brücke.

# CHAPTER V.

## *JUDGMENT OF DISTANCE AND SIZE.*

WE are now prepared to understand the modes of estimating *distance* and *size;* for these modes are founded partly on monocular and partly on binocular vision.

The eye perceives immediately direction up and down, and right and left; and therefore also outline-form and surface-contents—for these are but a combination of directions. Thus, two dimensions of space or angular diameter in all directions are directly given in sense. But this does not give *size*, unless distance in the line of sight, or depth of space, or third dimension is also known. Now, this third dimension is not given by sense, but is a judgment. As already stated, the direct and simple sense-impressions given by the optic nerve are *light*—its *intensity*, its *color*, and its *direction*. These can not be analyzed into any simpler elements. But *size*, *distance*, and *solid form* are judgments based on these direct gifts. Moreover, apparent size and estimated distance are strictly correlated with one another in such wise that a mistake in one necessarily involves a corresponding mistake in the other.

**Distance.**—We judge of distance by means of the different forms of perspective already described on page 161: 1. By *focal adjustment*, or monocular per-

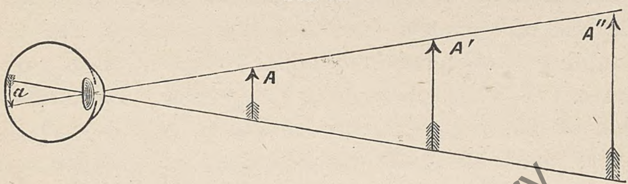
spective. The eye adjusts itself for distinct vision for all distances from infinite distance to five inches. By experience we know distance from the amount of effort necessary to adjust for perfect image, and therefore distinct vision. Judgments based on this are tolerably accurate from 5 inches to several yards. Beyond 20 feet it is too small to be appreciable. 2. By *axial adjustment*, or binocular perspective. The greater or less amount of optic convergence necessary to produce single vision is a far more accurate mode of judging of distance than the last. It is reliable from near the root of the nose to the distance of about a quarter of a mile. Beyond this it also becomes inappreciable, for the doubling of objects is only equal to the interocular distance. 3. By *mathematical perspective*. By diminution of the apparent size of known objects and the convergence of parallel lines we judge of distance with great accuracy and almost without limit. 4. By *aërial perspective*. Change of color and brightness of all objects, in proportion to the depth of air looked through, is still another mode of judging of distance, which, though far less accurate than the last, like it extends without limit. Estimates of distance, being judgments, are liable to error. Such errors are often called deceptions of sense, but they are not so. They are errors of judgment based upon *true deliverances* of sense.

**Size.**—The size of an unknown object is judged by its angular diameter, or the size of its retinal image multiplied by its estimated distance.* For example, an image *a*, Fig. 61, occupies a certain space on the retina.

* Hence magnification—which is only increase of retinal image—is equivalent to nearness of view. It is perfectly right to say of a telescope either that it increases the diameter of the moon five thousand times, or that it brings the moon within the distance of fifty miles. A myopic eye, therefore, magnifies every object.

Now, evidently, precisely the same image would be made by a small object at $A$, or a proportionally larger similar object at $A'$, or a still larger similar one at $A''$. Therefore the estimated size of the object which produced the image will depend wholly upon the distance we imagine the object to be from us, this distance being of course estimated by the different forms of perspective given above. Thus, estimates of size and distance are very closely related to each other, and an error in the one will involve an error in the other. If we misjudge

FIG. 61.




the distance of an unknown object, we will to the same degree and in the same direction misjudge its size: if our estimate of distance be too great, our judgment of size will also and to the same extent be too great; if our estimate of distance be two small, so also will be our judgment of size. Contrarily, if we make a mistake as to the size of a known object—as, for example, if we mistake a boy for a man—we will also to the same extent misjudge the distance. There is a *moral* as well as a physical perspective. A dollar may be held so near the eye or sit so near the affections as to cover and conceal the rest of the world. But in either case we must have an eye *single* to the dollar. The mind's eye, too, must be binocular or we get no true moral perspective.

Very many illustrations may be given of this general principle, but by far the most perfect are the ex-

periments on combination of the regular figures given on pages 133 and 134. In combining by squinting, in proportion as the point of optic convergence, and therefore the imagined place of the pattern, becomes nearer and nearer, the figures of the pattern become smaller. On the other hand, when we combine beyond the plane of the pattern, so that the more distant point of optic convergence makes the imagined place of the pattern farther off than its real place, then the figures are magnified in the same proportion. So also stereoscopic scenes are larger or smaller than the actual picture, according as we combine beyond or on this side the plane of the picture.

Illustrations like the above are most conclusive, because the relation of size and distance is seen to be mathematically proportioned: but many familiar illustrations may be given.

1. While intently regarding the paper on which I am writing, or the page which I am reading, a fly or gnat passes across the extreme margin of the field of view toward the open window. I mistake it for a large bird like a hawk flying at some distance in the open air. The reason is, that under these conditions we have no means of judging either of form or of distance; the size and distance of an object are therefore left wholly to the suggestions of the imagination. If we look around so as to see the form distinctly, and to bring binocular or other forms of perspective to bear on the subject, we quickly detect our error and correct our judgment.

2. Where there are no means of judging of distance, we can not estimate size, and different persons will estimate differently. Thus, the sun or moon seems to some persons the size of a saucer, to some that of a

dinner-plate, and to some that of the head of a barrel. But under peculiar conditions we imagine them much larger. For example, a pine-tree stands on the western horizon about a mile distant. I am accustomed to judge of the *size* and distance of trees. This one seems to me at least 20 feet across the branches. The evening sun slowly descends and sets behind the tree. It *fills and much more than fills its branches.* Does not the sun now seem 20 feet across? Again, here in Berkeley, on a clear day, the Farallone Islands, 40 miles distant, are distinctly seen through the Golden Gate. I think no one would say that the larger one seems less than 100 feet across. At certain seasons in spring and autumn the sun sets behind the Farallones, and these islands are projected in clear outline as black spots on his disk.

Again: if we gaze steadily at the setting sun until its image is well branded on the retina and then look down on a sheet of paper $2\frac{1}{2}$ feet away, the spectral image (the external projection of the brand) is a circle of about $\frac{1}{4}$ inch in diameter; looking at the wall 20 feet away, it is 2 inches in diameter; looking at a building 100 feet away, it is 10 inches in diameter. Now, this is about the size that the sun or moon in mid-sky seems to me. It would seem, then, that we usually project the retinal image of the sun or moon only about 100 feet.

3. Illustrations meet us on every side. In fog, objects look larger, because, through excess of aërial perspective, we overestimate distance. On the high Sierra, or the Colorado mountains, or anywhere on the high interior plateau, the clearness of the air and consequent distinctness of distant objects are such, that we imagine objects to be nearer and therefore smaller than they really are.

**Form.**—*Outline form* is a combination of directions of the component radiants. In a ring of stars, the direction of each star is given immediately; the combination of these several directions gives the ring. This is so simple and immediate a judgment, that it may almost be called a direct sense-perception. It is apparently a direct perception of the *form of the retinal image.* It is so sure and immediate that it is not liable to error; yet it is capable of analysis into simpler elements, as shown above.

*Solid form* is a far more complex judgment, and therefore liable to error. We judge of solid form partly by binocular perspective and partly by shades of light. The roundness of a column is perceived partly by the greater optic convergence necessary to see distinctly the nearer central parts than the farther marginal parts, and partly by the shading of light on the different parts. The latter effect can be perfectly imitated by the painter, but not the former. Hence the illusion produced by the painter is most perfect at a distance where binocular perspective is very small, but is destroyed by near approach. Hence also the roundness of a painted column is most perfect when looking with one eye, but of a natural column when looking with two eyes.

**Gradation of Judgments.**—*Intensity* and *color* are simple impressions which can not be further analyzed. *Direction* is already different and higher, since it is conditioned on space-perception, which is not a sensation. Still it also is simple and incapable of analysis. Next come *outline form* and *surface contents*, which may indeed be analyzed into combination of directions, but yet the perception is so direct and so certain that it may well be called immediate. Next comes *solid form*,

which, as we have seen, is a more complex judgment based on simple elements, and therefore may be deceived. Next come the closely related and still more complex judgments of *size and distance*, which are therefore still more liable to error. These latter judgments become more and more complex as the objects in the field of view become more numerous and more complex in form and varied in position; as, for example, the judgments of form, size, and distance of all the objects in an extended natural scene. All these seem to the uninstructed as immediate instinctive perceptions, and mistakes are supposed to be the result of deceptions of sense instead of errors of judgment, as they really are. Judgments like these, which are so quickly made that the process has largely dropped out of consciousness, I shall call *visual judgments*. But these higher and more complex visual judgments pass, by almost insensible degrees, into still higher and more complex *intellectual judgments*. Thus from simple sense-impressions we pass without break through the various grades of visual judgments to the lower intellectual judgments, and from these again through various grades of complexity to the highest efforts of the cultured mind.

Now, as visual judgments seem to the uninstructed primary, immediate, and simple perceptions, so also among intellectual judgments many seem to those uninstructed in psychology and unskilled in mental analysis as primary, immediate, instinctive, or innate, and therefore certain. But, as the study of visual phenomena teaches that these visual judgments are capable of analysis into simpler elements, and therefore liable to error, so also the study of psychology should teach us that many of the so-called instinctive judgments, pri-

mary intuitions, etc., may also be capable of analysis, and therefore liable to error. Further, it is evident that the so-called facts of consciousness, in the one field as in the other, can not be considered reliable until subjected to rigid analysis. The study of visual (especially binocular visual) phenomena is peculiarly valuable: first, in teaching us that so-called immediate intuitions are in many cases only judgments, the processes of which have dropped out of consciousness; and, second, in teaching us the habit of analysis of such apparently simple intuitions.

---

## RETROSPECT.

We have now given in clear outline the most important phenomena of vision and their explanation. It will not be amiss, before proceeding further, to look back over what we have passed, and justify its logical order.

There are three essentially different modes of regarding the eye, which must be combined in a complete account of this organ. We have taken up these successively. First, we treated of the *eye as an optical instrument* contrived to form a perfect image, every focal point of which shall correspond with a radiant point in the object. This is a purely physical investigation. Second, we treated of the *structure of the retina*, especially its bacillary layer, and showed how from this structure results the wonderful property of corresponding points *retinal* and *spatial*, and the exchange between these by impression and perceptive projection, and how the law of direction and all the phenomena of *monocular* vision flow out of this prop-

erty. Third, we treated of the still more wonderful correspondence of the *two retinæ* point for point, and of their spatial representatives point for point; and considered how by ocular motion the two images of the same object are made to fall on corresponding points of the two retinæ, and their spatial representatives are thereby made to coincide and become one; and how, finally, all the phenomena of *binocular* vision flow from this property.

We have therefore apparently covered the ground originally laid out. But there are still a number of questions on binocular vision, somewhat more abstruse and more disputed than the preceding, but of so high interest that they must not be wholly neglected. The remaining chapters will be devoted to these.

The conclusions reached on these points are almost wholly the result of my own investigations. They sometimes agree with those of other investigators and sometimes do not. They therefore rest on no higher authority than their own reasonableness. I bring them forward as an original contribution to the science of binocular vision, and invite the thoughtful reader to repeat the experiments and to verify or disprove the conclusions.

# PART III.

# ON SOME DISPUTED POINTS IN BINOCULAR VISION.

---

## CHAPTER I.

### *LAWS OF OCULAR MOTION.*

#### SECTION I.—LAWS OF PARALLEL MOTION.—LISTING'S LAW.

WE have already (page 63) spoken of spectral images produced by strong impressions on the retina. It is evident that these, being the result of impressions branded upon the retina and remaining there for some time, must while they remain follow all the motions of the eye with the greatest exactness. They are specially adapted, therefore, for detecting motions of the eyes, such as slight torsions or rotations on the optic axes, which could not be detected in any other way.

*Experiment 1.*—Let the experimental room be darkened by closing the shutters, but allow light to enter through a vertical slit between the shutters of one window. Standing before the window with head erect, gaze steadily at the slit until a strong impression is branded in upon the *vertical meridian* of the retina. If we now turn about to the blank wall, we see a very

distinct colored vertical spectral image of the slit. Placing now the eyes in the primary position—i. e., with face perpendicular and eyes looking horizontally —if, without changing the position of the head, we turn the eyes to the right or left horizontally, the image remains vertical. Also if we turn the eyes upward or downward by elevating or depressing the visual plane, the image remains vertical. But if, with the visual plane *elevated* extremely, say 40°, we cause the eyes to travel to the right or left, say also 40°, or if we turn the eyes from their original primary position obliquely upward and to one side to the same point, the image is no longer vertical, but leans decidedly to the *same* side; i. e., in going to the right, the image leans to the right, thus— / ; in going to the left, it leans to the left, thus— \ . If, on the contrary, the visual plane be *depressed*, then motion of the eyes to the right causes the image to lean to the left, thus— \ ; while motion to the left causes it to lean to the right, thus— / .

*Experiment 2.*—If, instead of a vertical, we use a horizontal slit in the window, and thus obtain a horizontal image and throw it on the wall as before, then, if the image has been made with the eyes in the primary position, it will be seen on the wall perfectly horizontal. Furthermore, if the eyes travel right and left in the primary visual plane, or upward and downward by elevating or depressing the visual plane, the image retains its perfect horizontality. But if, with the visual plane elevated, we cause the point of sight

to travel to the one side or the other, the image is seen to turn to the *opposite* side; i. e., when the eyes turn to the right, the image turns to the left, thus— ; when they turn to the left, the image rotates to the right, thus— . If the visual plane be *depressed*, then motion to the right causes the image to rotate to the right, , and motion to the left causes it to rotate to the left, .

These rotations of the image depend wholly on the oblique position of the eyes, and it makes no difference how that oblique position is reached—whether by motion along rectangular coördinates, as in the experiments, or by oblique motion from the primary position. Furthermore, the amount of rotation of the image increases with the amount of elevation or depression of the visual plane, and the amount of lateral motion of the eyes.

*Experiment 3.*—The fact of rotation or torsion of the images, and the direction of that torsion, are easily determined by the somewhat rough methods detailed above; but if we desire to *measure the amount of torsion*, the wall or other experimental plane must be covered with rectangular coördinates, vertical and horizontal. By experimenting in this way, I find that for extreme oblique positions the torsion of the vertical image on the vertical lines of the experimental plane is about 15°, but the torsion of the horizontal image on the horizontal lines is only about 5°. The reason of this difference will be explained farther on.

Putting now all these results together, the following diagram (Fig. 62) gives the position of the vertical and horizontal images when projected on a vertical plane for all positions of the point of sight. Simple inspection of the diagram is sufficient to show

that the inclination or torsion of the vertical image on the true verticals, and that of the horizontal image on the true horizontals, are in *opposite directions*. If torsion

FIG. 62.

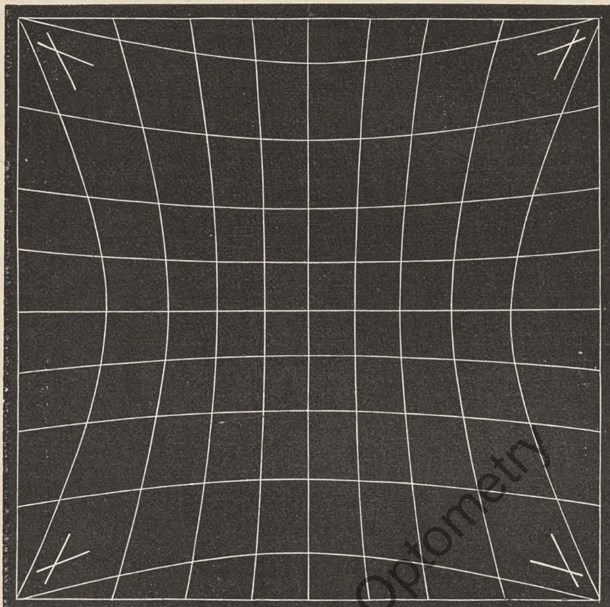
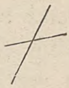


DIAGRAM SHOWING THE INCLINATION OF VERTICAL AND HORIZONTAL IMAGES FOR ALL POSITIONS OF THE POINT OF SIGHT, WHEN PROJECTED ON VERTICAL PLANE.

of the images show torsion of the eye, there must be a fallacy somewhere. The one or the other must be wrong; for when one indicates torsion to the right, the other indicates torsion to the left, and *vice versa*. To show this contradictory testimony more clearly, and thus to prove that there is a fallacy here, we make another experiment.

*Experiment 4.*—Make a rectangular cross-slit in the window, gaze steadily upon it until the spectral impres-

sion is made on the retina, and then cast the image on the wall. In the primary position of the eyes it is of course a perfect rectangular cross. Now turn the eyes to the extreme upper right-hand corner of the wall. The cross, by opposite rotations of the two parts, is seen distorted thus— . Looking upward and to the left, it is seen thus— . Oblique motion downward and to the right makes it appear thus— , and to the left thus— . It will be observed that this is exactly the manner in which the lines cross in the diagram, and we have placed crosses in the corners to indicate that fact.

Evidently the cause of the contradictory evidence of the two images is *projection* on a plane inclined at various angles to the line of sight. The diagram is a correct representation of the phenomena as seen projected on a vertical plane, but is not a correct representation of the torsions of the eyes. To eliminate this source of fallacy and get the true torsion of the eyes, we must project the cross-image on a plane in every case perpendicular to the line of sight.

*Experiment 5.*—Prepare an experimental plane a yard square, make a rectangular cross in the center, and set up a perfectly perpendicular rod at the point of crossing. Fix the plane in a position inclined 30° to 40° with the vertical, and obliquely to the right side and above, so that, when sitting before the experimental window and turning the eyes extremely upward and

to the right, the observer looks directly on the top of the rod, and this latter is projected against the plane as a round spot. We thus know that the line of sight is perpendicular to the plane. Now, after gazing at the cross-slit in the window until the spectral impression is made on the retina, without moving the head, cast the image on the center of the plane by turning the eyes obliquely upward and to the right. The rectangular cross-image rotates, *both parts alike*, so as to retain perfectly its rectangular symmetry, to the right, thus—

, showing unmistakably a torsion of the eyes in the same direction. If the plane be arranged similarly on the left side, the cross turns to the left, thus— . If the plane be arranged below and to the right, so that the eyes turned obliquely downward and to the right shall look perpendicularly upon it, the cross will turn to the left, thus— . If similarly arranged on the left side, the cross will turn to the right, thus— . In all cases the rectangular symmetry is perfectly preserved, a sure sign that there is no error by projection, and that they truly represent the torsion of the eyes.

*Experiment 6.*—In order to neglect no means of testing the truth of this conclusion, we will make one more experiment, using the sky as the plane upon which to project the image. This spatial concave is of course everywhere at right angles to the line of sight, and therefore is free from any suspicion of error from projection. Standing in the open air before a vertical

flag-staff, I gaze upon it steadily until its image is, as it were, burned into the vertical meridian of the retina. Now, without moving the head, I turn the eyes obliquely upward and to the right, and the image leans decidedly to the right; and turning to the left, the image leans to the left. In this position of the head, of course, the ground prevents us from making the same experiment with the visual plane depressed. I therefore vary the experiment slightly. Sitting directly in front of the college building, with the morning sun shining obliquely on its face, the light-colored perpendicular pilasters gleam in the sunshine, and contrast strongly with the shadows which border their northern margin. Gazing steadily at the building, I easily get a strong spectral image of the whole structure, with its vertical and its horizontal lines. Now throwing myself flat on my back, I see the image perfectly erect on the zenith. Turning the eyes upward toward the brows and to the right and left, then downward toward the feet and to the right and left, the whole image of the building rotates precisely as indicated in my previous experiments.

Evidently, then, in the diagram Fig. 62, the *verticals* give true results, but the *horizontals* deceptive results by projection. Why this is so is easily explained. Suppose an observer to stand in a room before a vertical wall; suppose him further to be surrounded by a spherical wire cage constructed of rectangular spherical coordinates, or meridians and parallels, with the eye in the center and the pole in the zenith. Evidently, the surface of this spherical concave is everywhere perpendicular to the line of sight, and therefore, like the sky, is the proper surface of projection. Evidently, also, the meridians and parallels everywhere at right angles to

each other are the true coördinates wherewith to compare the images, vertical and horizontal, in order to determine the direction and amount of their rotation. Now the simple question is, "How do these true rectangular coördinates project themselves on the wall to an eye placed in the center, or how would their shad-

Fig. 63.

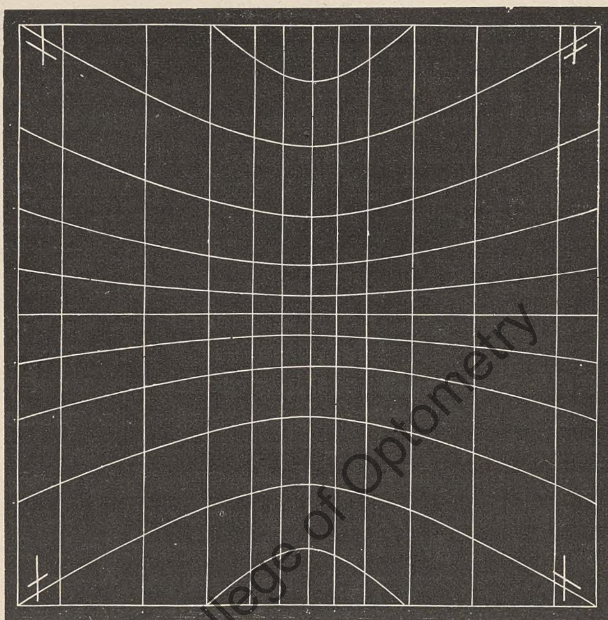
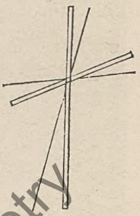


Diagram showing the Projection of a System of Spherical Coördinates on a Vertical Plank.

ows be cast by a light in the center?" It is evident that the meridians would project as straight verticals, but the parallels not as straight lines, but as *hyperbolic curves*, increasing in curvature as we go upward or downward. The diagram Fig. 63 shows how the

spherical coördinates would project on a vertical wall. By calculation or by careful plotting it may be shown that at an angle of elevation or depression of 40°, and a lateral angle of the same amount, the inclination of the hyperbolic curve on the horizontals of the wall will be about 20°. Now a rectangular cross-image, if *unrotated*, would project as the crosses in the corners, i. e., the vertical arm would project vertically, but the horizontal arm would be inclined 20° with the horizontal, so that the angles of the cross would be about 70° and 110°. Now rotate these crosses 15°, the right upper one to the right, the left upper one to the left, the right lower to the left, and the left lower to the right, and we have the precise phenomena represented by the diagram Fig. 62; i. e., the verticals are turned 15° right or left as the case may be, and the horizontals in the opposite direction but only 5°. Fig. 64 illustrates this in the case of the right-hand upper cross-image—the heavy cross representing the cross unrotated, and the lighter one the same rotated 15° to the right by extreme obliquity of the line of sight.

FIG. 64.



Therefore, the diagram which truly represents the torsion of the eye in various positions, or the torsion of the cross-image when referred to a spherical concave perpendicular to the line of sight in every position, is represented in Fig. 65. Simple inspection of this figure shows the real direction and amount of rotation both of the vertical and the horizontal image for every position of the line of sight. The crosses in the corners show that there is no distortion by projection.

We are justified therefore in formulating the laws of parallel motion of the eyes thus:

1. *When the eyes move together in the primary plane to the one side or the other, or in a vertical plane up or down, there is no rotation on the optic axes, or torsion.*

FIG. 65.

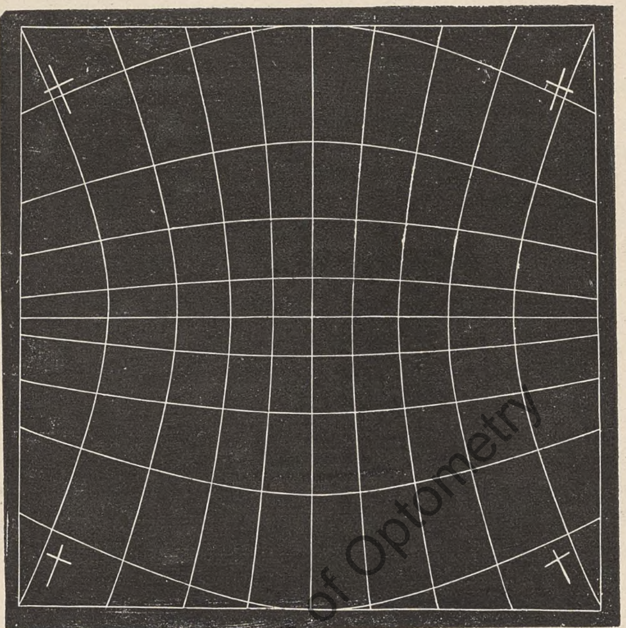


DIAGRAM SHOWING THE TRUE TORSION OF THE EYE FOR VARIOUS POSITIONS OF THE POINT OF SIGHT.

2. *When the visual plane is elevated and the eyes move to the right, they rotate to the right; when they move to the left, they rotate to the left.*

3. *When the visual plane is depressed, motion of the eyes to the right is accompanied with rotation to the left, and motion to the left with rotation to the right.*

4. These laws may be all generalized into one, viz.: *When the vertical and lateral angles have the same*

*sign,* the rotation is positive* (*to the right*); *when they have contrary signs, the rotation is negative* (*to the left*).

The law now announced as the result of experiment is evidently identical with the *law of Listing*, which has been formulated by Listing himself thus:

"*When the line of sight passes from the primary position to any other position, the angle of torsion of the eye in its second position is the same as if the eye had come to this second position by turning about a fixed axis perpendicular both to the first and the second position of the line of sight.*" †

Now an axis which satisfies these conditions can be none other than an *equatorial axis*—i. e., *an axis in a plane perpendicular to the polar or visual axis.* In turning from side to side in the primary plane, it is a vertical equatorial axis. In turning up and down vertically, it is a horizontal equatorial axis. In turning obliquely, as in the experiments on torsion, it is an oblique equatorial axis. Now take a globe, and, placing the equator in a vertical plane, make a distinct vertical and horizontal mark across the pole. Then turn the globe on an oblique equatorial axis, so that the pole shall look upward and to the right. It will be seen that the polar cross is no longer vertical and horizontal, but is *rotated to the right.* If the globe be turned upward and to the left, the polar cross will rotate to the left; if downward and to the right, it will rotate to the left; and if to the left, it will rotate to the right. In a word, the rotation in every case is the same as given in the above laws determined by experiment.

* In reference to a vertical line, positions to the right are positive and to the left negative; in reference to a horizontal line, above is positive and below negative.

† Helmholtz, "Optique Physiologique," p. 606.

**Contrary Statement by Helmholtz.**—We have given these laws and their experimental proof in some detail, and have taken some pains to show that they are in complete accord with Listing's law, because Helmholtz in his great work on "Physiological Optics" has given these laws of ocular motion the very reverse of mine. I quote from the French edition of 1867, which is not only the latest but also the most authoritative edition of the work: *

"When the plane of sight is directed upward, lateral displacements to the *right* make the eye turn to the *left*, and displacements to the left make it turn to the *right*.

"When the plane of sight is depressed, lateral displacements to the *right* are accompanied with torsion to the *right*, and *vice versa*.

"In other words, when the vertical and lateral angles are both of the same sign, the torsion is *negative*; when they are of contrary signs, the torsion is *positive*." †

We have demonstrated the very reverse of every one of these propositions, and we have also shown that they are inconsistent with Listing's law as quoted by Helmholtz himself. The experiments by which Helmholtz seeks to determine the torsions of the eye are the same as those already described under experiments 1 and 2, pages 185 and 186. The results which he reaches are also the same as those reached by myself, except that he makes the inclination of the vertical image on the verticals of the wall, and of the horizontal image on the horizontals of the wall, equal to each other, while I make the inclination of the verticals much greater. The diagram by which he embodies all these results is also

* A short time before his death Helmholtz commenced a revision of his great work, but he never finished, and, as I learn from his translator, Javal, he never altered these statements.

† "Optique Physiologique," p. 602.

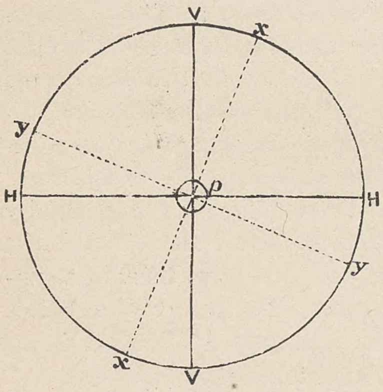
similar to my diagram, Fig. 62, except that in his the horizontal and vertical curves are exactly similar, while in mine the curves of the verticals are much greater. He also, like myself, admits that there is a fallacy by projection. But unaccountably he imagines that the inclination of the horizontal image on the true horizontal gives true results, and the inclination of the vertical image on the true vertical deceptive results by projection; therefore he imagines the eye to turn exactly the reverse of the reality. Experiments 5 and 6, under conditions eliminating errors by projection, prove the falseness of his results. I have striven in vain to find some explanation of Helmholtz's statements, and especially concerning the contrary rotations of the vertical and horizontal images. I can not but regard them as a simple mistake by inadvertence. The reader who desires to follow up this subject will find it discussed in an article by the writer referred to below.*

**The Rotation only Apparent.**—There can be no doubt, then, that when the eye passes from its primary position to an oblique position, the vertical meridian of the retina is no longer vertical, but inclined. If we observed the iris of another person, we should see that it had turned as a wheel. In deference to the usage of other writers and to the appearance, I have spoken of this as a *rotation on the optic axis*, but it is so in appearance only, and not in reality; for the motion of the eye, being always on an axis *in a plane perpendicular to the polar or optic axis*, can not be resolved into a rotation about that axis. A simple experiment will show the kind of rotation which takes place in bringing the eye to an oblique position. Take a circular card, Fig. 66, and make on it a rectangular cross which shall rep-

* "American Journal of Science and Arts," III, vol. xx, 1880, p. 83.

resent the vertical ($V\ V$) and horizontal ($H\ H$) meridians of the retina. A small central circle $p$ represents the pupil. Now take hold of the disk with the thumb and finger of the right hand at the points $V\ V$, and place this line in a vertical plane. Then tip the disk up so that the pupil $p$ shall look upward 45° or more, but the line $V\ V$ still remaining in the vertical plane. Finally, with the finger of the left hand turn the disk on the axis $V\ V$ to the left. It will be seen that $V\ V$ is no longer vertical, nor $H\ H$ horizontal; but some other line $x\ x$ is vertical, and $y\ y$ horizontal. In other words, the whole disk seems to have rotated to the left. But this is evidently *no true* rotation on a polar axis, but only an *apparent* rotation consequent upon *reference to a new vertical meridian of space*. It does not take place in the primary plane, because there all the spatial meridians are parallel, but only in an elevated or depressed plane, because the spatial meridians are there convergent to poles in the zenith and nadir.

Fig. 66.




After this discussion it may be well to redefine the law of Listing in different words, thus: When the eye passes from its primary position to any other position, it always turns on some equatorial axis, or axis at right angles to the visual axis, but "never swivel-like on the visual axis itself."* I shall therefore hereafter call this

* Foster, "Physiology," Part IV, p. 1279.

apparent rotation on the visual axis *torsion*. This is the more important, because there is a real rotation on the visual axis, which we shall speak of under the next head.*

---

## SECTION II.—LAWS OF CONVERGENT MOTION.

We have thus far confined ourselves to explanation of the laws which govern the eyes when they move in the *same direction* with axes parallel, as in looking from side to side or up and down. I have called this the law of *parallel motion*. We now come to speak of the laws which govern the eyes when they move in *opposite directions*, as in convergence. These I shall call the laws of *convergent motion*.

In convergence there is not merely an *apparent* rotation or torsion, but a *real* rotation of the eyes on the optic or visual axes; and since the motions are in *opposite* directions, the rotations are also opposite. But, except in very strong convergence, the rotation is small and difficult to observe, and therefore has been either overlooked or denied by many observers. As the existence or non-existence of this rotation has an important bearing on the much-vexed question of the horopter, it is important that proof should be accumulated even to demonstration.

The first difficulty which meets us in experimenting on this subject is, that spectral images, which are such delicate indicators of ocular motion, are almost useless here. In parallel motion of the eyes these images follow every movement with the utmost exactness, but in convergent motion they do not. Suppose, for example, with the eyes parallel or nearly so, a spectral image is

* I am indebted to Mrs. Franklin for having drawn my attention to the fact that several writers, Volkmann, Donders, Aubert, etc., have perceived that the rotation of the eyes in Helmholtz's experiments is only apparent.

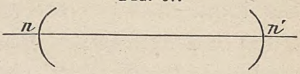
branded on the vertical meridians of both eyes. In convergence each eye may move through 45° or more, and yet the place of the spectral image remains the same, viz., *directly in front*. The eye also in extreme convergence may rotate on the optic axis 10°, but the vertical image remains still perfectly vertical. The reason of this is, that the two retinal images are on corresponding points, and therefore by the law of corresponding points their external representatives are *indissolubly united.* In moving the eyes in opposite directions, it is impossible that the images should move except by separating; but separation, either complete or partial, is impossible without violating the law of corresponding points—a law which is never violated under any circumstances whatsoever. Actual objects therefore, not spectral images, must be used in these experiments.

As the experiments about to be described are among the most difficult in the whole field of binocular vision, and as in many of them it is absolutely necessary that the primary visual plane should be perfectly horizontal, I must first define what we mean by the *primary visual plane*, and show how it may be made perfectly *horizontal.*

Take a thin plate, like a cardboard; place its edge on the root of the nose and the card at right angles to the line of the face, in such wise that the plane of the card shall cut through the center of the two pupils, and you can see only its edge. The card is then in the primary visual plane. Keeping the position of the card fixed in relation to the face, the face may be elevated or depressed, and the card will be also elevated or depressed, but will remain in the primary visual plane. But if the card be elevated or depressed so as to make a different angle with the line of the face, then the visual plane is elevated or depressed above or below the

primary position. When the head is erect and the line of the face vertical, the primary visual plane is horizontal. Suppose we wish now to look at a vertical wall in such wise that the primary visual plane shall be perfectly horizontal. We first mark on the wall a horizontal line

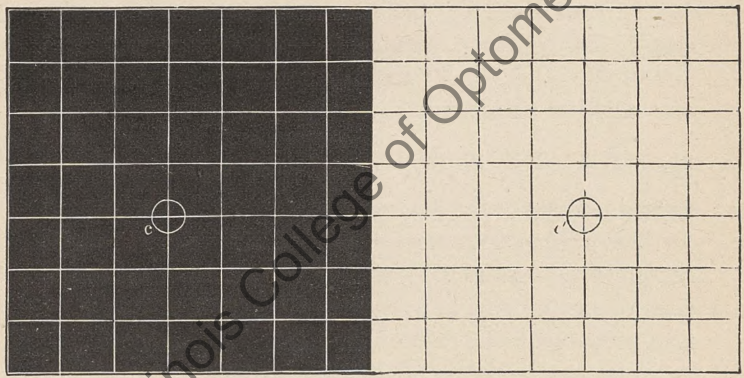
Fig. 67.



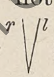

exactly the height of the root of the nose. Standing then say 6 feet off, and shutting first one eye and then the other, we bring the image of the lowest part of the root of the nose directly across the line. The primary plane is then perfectly horizontal. In Fig. 67, $n$ and $n'$ are the curves of the outline of the root of the nose as seen by the right and left eye respectively, and $n\ n'$ is the horizontal line on the wall. We are now prepared to make our experiments.

*Experiment 1.*—Prepare a plane 2 feet long and 1 foot wide. Dividing this by a middle line into two

Fig. 68.



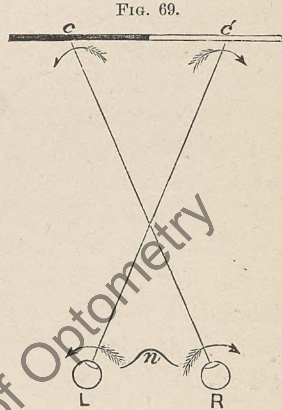

equal squares, let one of the halves be painted black and the other white. Let the whole be covered with rectangular coördinates, vertical and horizontal, on the

black half the lines being white and on the white half black, as in Fig. 68. Near the middle of the two square halves, and at the crossing of a vertical and horizontal line, make two small circles, $c\ c'$. Set up this plane on the table in a perfectly vertical position, and at a distance of 2 or 3 feet. Rest the chin on the table immediately in front of the plane, with a book or other support under the chin, so that the root of the nose shall be exactly the same height as the circles, which in this case is about 6 inches. Now, shutting alternately one eye and the other, bring the image of the lowest part of the root of the nose coincident with the horizontal line running through the circles. The primary plane is now perfectly horizontal, and therefore at right angles to the experimental plane. Now, finally, converge the eyes until the right eye looks directly at the left circle, and the left eye at the right circle, and of course the two circles combine. If one is practiced in such experiments, and observes closely, he will see that the vertical lines of the two squares (which can be readily distinguished, because those of the one are white and of the other black), as they approach and pass over one another successively, are not perfectly parallel, but make a small angle, thus—  ; and also that the angle increases as the convergence is pushed farther and farther so that lines even beyond the circles are brought successively together. Similarly also the horizontals cut each other at a small angle, but this fact is not so easy to observe as in the case of the verticals.

Such are the phenomena; now for the interpretation. It must be remembered that images of objects differ wholly from spectral images in this, viz.: that spectral images, being fixed impressions on the retina, follow

the motions of the eye with perfect exactness; while, images of objects being movable on the retina, their external representatives in convergence seem to move in a direction contrary to the motions of the eye (page 124). This is true of all motions, whether by transfer of the point of sight or by rotation about the optic axes. Now, in the above experiment, the images of the two squares with all their lines seem to rotate about the point of sight outward—i. e., the right-hand square to the right, and the left-hand square to the left. At first sight this might seem to indicate a contrary rotation of the eyes, viz., inward. But not so; for, observe, the field of view of the right eye is the left or black square, and the field of view of the left eye is the right or white square. The right-eye field turns to the left, showing a rotation of the right eye to the right; while the left-eye field turns to the right, showing a rotation of the left eye to the left. *Thus the two eyes in convergence rotate outward.* This is shown in the diagram Fig. 69, in which $c$ $c'$ is the experimental plane. The arrows show the direction of rotation of the images of the plane and of the eyes.

Fig. 69.




*Experiment 2.*—When one becomes accustomed to experiments of this kind, he can make them in many ways. I find the following one of the easiest and most convenient: Measure the exact height of the root of the nose upon the sash of the open window, and mark it. Stand with head erect about 3 or 4 feet from the window. Using the cross-bars of the sash-frame as hori-

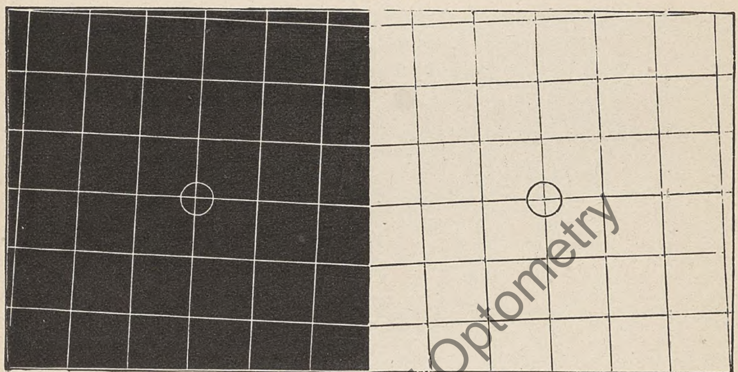
zontal lines, arrange the head so that the two images of the root of the nose shall be exactly the same height as the mark. The primary plane is now horizontal. Now converge the eyes until the dark outer jambs or sides of the frame of the sash approach each other. This will be very distinct on account of the bright light between them. It will be seen that the frames come together, not parallel, but as a sharp V, thus— $^{r}\backslash\,/^{l}$, *r* and *l* being the right- and left-eye images respectively. I find that when I stand at a distance from the window equal to the width of the sash, the angle between the two jambs as they come together is about 15°, showing a rotation of each eye outward 7° 30′. When standing still nearer, so that the convergence is extreme, the angle is 20° or more, showing a rotation of each eye of 10° or more.

In all these experiments the extremest care is necessary to insure the perfect horizontality of the visual plane. The slightest upward or downward looking vitiates the result by introducing mathematical perspective. If there were no rotation, then looking upward and converging would bring the jambs together by perspective, thus— $_{r}/\,\backslash_{l}$; looking downward, thus— $^{r}\backslash\,/^{l}$; looking horizontal, parallel, thus— $||$. But on account of rotation, looking horizontal brings them together thus— $^{r}\backslash\,/^{l}$; downward, at higher angle, thus— $^{r}\backslash\,/^{l}$. Looking upward more and more, the angle decreases till it becomes 0 (i. e., the jambs parallel), and then inverted. I find that in the previous experiment, standing from the window the distance of its width, I must

elevate the plane of vision about 6°—i. e., I must look about 8 or 9 inches above the mark—to make the jambs parallel. This is therefore a good method of measuring amount of rotation.

*Experiment 3.*—A far more accurate mode of measuring the amount of rotation is by constructing diagrams on a plane similar to the one used in experiment 1, but in which the verticals and horizontals are both inclined on the true verticals and true horizontals in a direction contrary to the rotation of the eyes—i. e., in-

FIG. 70.



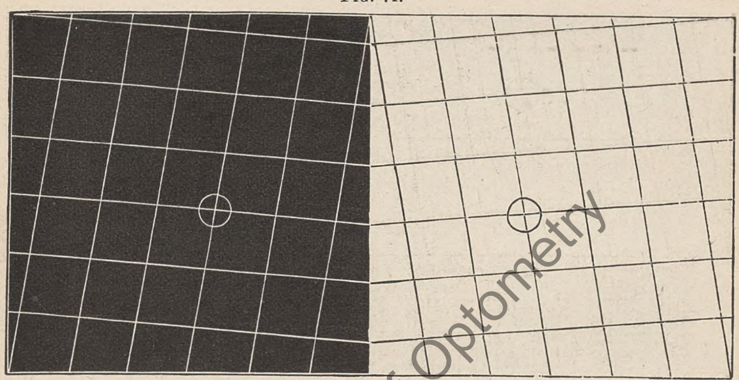
VERTICALS AND HORIZONTALS INCLINED $1\frac{1}{4}$°.

ward—and then determining the degree of convergence necessary to make them come together *perfectly parallel.* I find that for my eyes, when the verticals are thus inclined in each square $1\frac{1}{4}$° with the true vertical, and therefore make an angle of $2\frac{1}{2}$° with each other (Fig. 70), they come together parallel when the point of sight is 7 inches from the root of the nose. When the angle of inclination in each is $2\frac{1}{2}$° with the true vertical, and therefore 5° with each other, the point of sight must be 4 inches off. When the inclination with

15

the true vertical is 5°, and therefore 10° with each other, the point of sight is 2·2 inches. Finally, when the inclination with the true vertical is 10°, or 20° with each other, then they can be brought together parallel only by the extremest convergence, the point of sight being then only a quarter of an inch in front of the root of the nose. In the diagram Fig. 70 the lines, both vertical and horizontal, are inclined inward $1\frac{1}{4}$°, and therefore the verticals of the two squares make an angle with each other of $2\frac{1}{2}$°. It is therefore a reduced facsimile of the

Fig. 71.

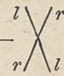


Verticals inclined 10°, Horizontals 5°.

plane used. The coördinate lines coincide when the point of sight is 7 inches from the root of the nose.

In the cases of extreme convergence mentioned above, I find that for perfect coincidence of both verticals and horizontals it is necessary that the inclination of the verticals with the true vertical must be greater than that of the horizontals with the true horizontal; so that the little squares are not perfect squares. Thus, when the verticals incline 5°, the horizontals must incline only $3\frac{3}{4}$°; when the verticals incline 10°, the horizontals

incline only 5°. Fig. 71 is a reduced facsimile of the experimental plane used in this last case of extreme convergence. I can not account for this, except by a distortion of the ocular globe by the unusual and unnatural strain on the muscles, especially the oblique muscles of the eyes. It may be that other eyes are more rigid than mine, and suffer less distortion.

The above is by far the most refined method of proving rotation, and of measuring its amount. But so difficult are these experiments, and so delusive the phenomena, that it is necessary to prove it in many ways. Another method is by means of *ocular spectra.* We have already shown that these are not so well adapted to experiments in convergent motion as they are in parallel motion. For example, two brands on the vertical meridians of the two retinæ produce spectral images which are perfectly united (pages 199 and 200). Now in strong convergence, when the two eyes rotate outward, the two images will not separate or cross each other, thus— 

, as we might at first expect; for this is forbidden by the law of corresponding points. But we may use a spectral image of *one* eye to show rotation of that eye.

*Experiment 4.*—The manner in which I conduct the experiment is as follows: I make a vertical spectral

FIG. 72.

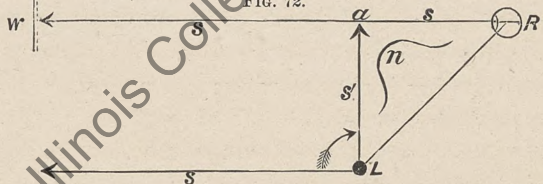



image in the manner already explained (page 185), by gazing with one eye (say the right) on a vertical slit in

a closed window. I now turn about, and, keeping the left eye $L$, Fig. 72, still shut, I look across the root of the nose $n$ with the right eye $R$ at a perfectly vertical line $w$ on the wall. I see the vertical image perfectly parallel and nearly coincident with the vertical line on the wall. Then, while the right eye still continues to look along the line $R\ s$, I turn the shut left eye $L$ from its previous position $L\ s$ through an angle of 90°, until its line of sight is $L\ s'\ a$. In other words, I run the *point of sight* or point of convergence from the distant point of the wall $w$ along the line $R\ s$ to the point $a$ near the root of the nose. When I do so, I see the spectral image incline to the right, thus—/, indicating (since the image is *spectral*) a rotation of the eye in the *same* direction. This experiment is very difficult, but it is conclusive.

*Experiment 5.*—I shut one eye, say the left, and look across the root of the nose at a distant object, as in Fig. 72 $W$. An assistant now observes attentively my iris, and notes with care the position of the radiating lines. Now, without changing at all the direction of the *line* of sight, I change the *point* of sight to an object or point very near the root of the nose, as in Fig. 72, by turning the optic axis of the shut eye through 90° to $a$. I again relax the convergence so as to make the optic axes *parallel*, and again converge upon the near point; and so on alternately. With every convergence the iris is seen to rotate like a wheel *outward*. I have subjected my eyes to the observation of five different persons, and they all made the same statement in regard to the direction of rotation.

There can be no longer any doubt that *my* eyes in convergence rotate on the optic axes outward, the de-

gree of rotation increasing with the degree of convergence. To generalize this as a law of ocular motion I have found extremely difficult, because there are so few persons who are able to verify the results, on account of imperfect voluntary control of the ocular muscles, and especially the difficulty or even impossibility which most persons find in observing intelligently images which are not at the point of sight. Nevertheless, I have found several persons who by considerable practice have been able to confirm nearly all these experiments. I have also made observations directly on the eyes of other persons in the manner described in the fifth experiment, and noted the rotation of the iris in strong convergence. I think, therefore, I am justified in announcing the outward rotation of the eyes in convergence as a general law.

**The Effect of Elevation and Depression of the Visual Plane on Rotation.**—The question next occurs, What is the effect, on this rotation, of elevation or depression of the visual plane? I have also made many experiments to determine this point.

*Experiment 6.*—In making experiments of this kind, all that is necessary is that the experimental plane shall be exactly perpendicular to the visual plane. This may be insured either by keeping the face in its former position and changing the inclination of the plane, or else, more conveniently, by fixing the plane in its vertical position and changing the inclination of the face. If we choose the latter method, then, for experiments with the visual plane elevated, the head or face is turned downward and the eyes look upward toward the brows upon the experimental plane —care being taken that the eyes in their new position shall be on a level with the center of the plane. By

experiments of this kind I find that the outward rotation in convergence, especially in strong convergence, *increases* decidedly for the same degree of convergence with the elevation of the visual plane.

*Experiment 7.*—For experiments on rotation with the visual plane depressed, the face must be turned upward (taking care as before that the eyes in their new position are on a level with the center of the plane), and then the eyes look downward toward the point of the nose upon the experimental plane. In this case I find that for the same degree of convergence the rotation decreases steadily, until it becomes zero for all degrees of convergence when the visual plane is depressed 45° below its primary position—i. e., when the eyes look toward the point of the nose. Below this angle the rotation seems to be inverse—i. e., inward—although it is impossible to try this with strong convergence, because the nose is in the way.

**Cause of the Rotation.**—It is probable that the rotation is produced by the action of the inferior oblique muscles. If so, we can understand why it increases with elevation of the visual plane, and decreases with its depression; for in the first case the tension on these muscles would be increased, while in the latter case it would be decreased.

**Previous Researches on this Subject.**—At the time of my own researches in 1867 * the only writer who to my knowledge had made experiments on the rotation of the eyes on the visual axes in convergence was Meissner.† Since that time I find that Hering and others have done so. The results Meissner arrives at are substantially the same as my own; but he arrives

* "American Journal of Sciences," vol. xlvii, pp. 68 and 153, 1869.
† "Archives des Sciences," tome iii, 1858, p. 160.

at them indirectly, while investigating the question of the horopter, and by methods far less exact than those employed by myself. My results, therefore, must be regarded as a confirmation and a demonstration of his. Meissner's method will be spoken of under the head of the horopter.

**Laws of Parallel and of Convergent Motion Compared.** —We will now formulate the laws of convergent motion, and at the same time contrast them with those of parallel motion.

1. When the eyes move in the primary plane in the *same* direction (parallel motion), *there is no torsion;* but when they move in that plane in *opposite* directions, as in convergence, they *rotate outward.*

2. When the visual plane is *elevated* and the eyes move in the same direction by *parallel* motion, then lateral motion to the *right* produces torsion to the *right*, and to the *left*, torsion to the *left;* but when, on the contrary, they move in opposite directions, as in *convergence*, then as the right eye moves to the *left*, i. e., toward the nose, it rotates to the *right*, and as the left eye moves toward the nose, i. e., to the *right*, it rotates to the *left*. If Listing's law operated at all in this case, as it acts in the opposite direction, it would tend to neutralize the effects of convergent rotation; but such is not the fact. On the contrary, as we have seen, the outward rotation increases with elevation of the visual plane.

3. When the visual plane is *depressed*, and the eyes move from side to side by *parallel* motion, then lateral motion to the *right* is attended with torsion to the *left*, and motion to the *left* with torsion to the *right*. Also when the eyes move by *convergent* motion in opposite directions, they rotate in the same direction as in the

case of parallel motion; but there is this great difference: that while in parallel motion the *torsion increases* with the angle of depression, in convergent motion *rotation decreases* to zero at 45°. If Listing's law operated at all in this case, it would coöperate with and increase the effect of convergent motion; but the very reverse is the fact, the rotation decreasing with the angle of depression.

4. We have already shown that the so-called torsion of parallel motion is not a true rotation on the optic axes, but only an *apparent* rotation, the result of reference to a new spatial meridian not parallel with the primary meridian. On the contrary, the rotation produced by convergent motion is a *true* rotation on the optic axes, as shown by the fact that one eye without change of position will rotate in sympathy with the convergent motion of the other eye (experiments 4 and 5).

It is evident, then, that when the eyes move in the same direction parallel to each other, as in ordinary vision of distant objects, then all their motions are governed by Listing's law; but when, on the contrary, they move in opposite directions, as in convergence, then the law of Listing is either greatly modified or else it is overborne, and another law reigns in its place.

## CHAPTER II.

### *THE HOROPTER.*

IF we look at any point, the two visual lines converge and meet at that point. Its two images therefore fall on corresponding points of the two retinæ, viz., on their central spots. A small object at this point of convergence is seen absolutely single. We have called this point "the point of sight." All objects beyond or on this side the point of sight are seen double—in the one case homonymously, in the other heteronymously—because their images do not fall on corresponding points of the two retinæ. But objects below or above, or to one side or the other side of the point of sight, may possibly be seen single also. *The sum of all the points which are seen single while the point of sight remains unchanged is called the horopter.*

Or it may be otherwise expressed thus: Each eye projects its own retinal images outward into space, and therefore has its own field of view crowded with its own images. When we look at any object, we bring the two external images of that object together, and superpose them at the point of sight. Now the point of sight, together with the images of all other objects or points which coalesce at that moment, lie in the horopter. The images of all objects lying in the horopter

fall on corresponding points, and are seen single; and conversely, the horopter is the surface (if it be a surface) of single vision.

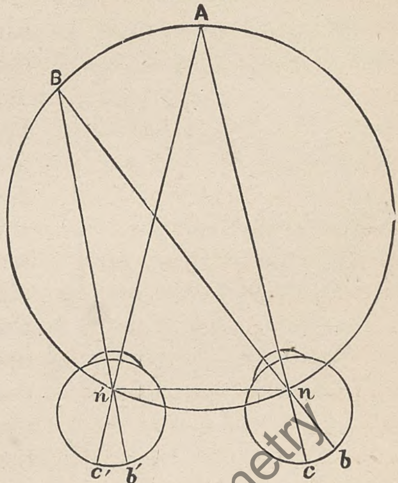
Is the horopter a *surface*, or is it only a *line?* In either case, what are its form and position? These questions have tasked the ingenuity of physicists, mathematicians, and physiologists. If the position of corresponding points were certainly known, and if the meridians of the eye in all its motions corresponded perfectly with the spatial meridians, then the question of the horopter would be a purely mathematical one. But the position of the ocular meridians, and therefore of corresponding points, may change in ocular motions. It is evident, then, that it is only on an experimental basis that a true theory of the horopter can be constructed. And yet the experimental determination, as usually attempted, is very unsatisfactory on account of the indistinctness of perception of objects except very near the point of sight. Therefore experiments determining the laws of ocular motion, and mathematical reasoning based upon these laws, seem to be the only sure method.

The most diverse views have therefore been held as to the nature and form of the horopter. Aguilonius, the inventor of the name, believed it to be a *plane* passing through the point of sight and perpendicular to the median line of sight. This, as we have shown (page 117, Fig. 40), is geometrically untenable. Others have believed it to be the *surface of a sphere* passing through the optic centers and the point of sight; others, a *torus* generated by the revolution of a circle passing through the optic centers * or nodal points and the point of sight (horopteric circle of Müller), about a line joining the

* Optic center is here used in sense of center of the lens system, not of the ocular globe.

optic centers. The subject has been investigated with great acuteness by Prévost, Müller, Meissner, Claparède, and finally by Helmholtz. Prévost and Müller determine in it, as they think, the circumference of a circle passing through the optic centers and the point of sight (the horopteric circle), and a line passing through the point of sight and perpendicular to the plane of the circle (horopteric vertical). The horopteric circle of Müller is shown in Fig. 73, in which $n\,n'$ is the line between the nodal points or points of ray-crossing, $A$ the point of sight, and $B$ an object to the left and situated in the circumference of the circle. Of course, the images of $A$ fall on the central spots $c\,c'$. It is seen also that the images of $B$ fall at $b\,b'$, at equal distances from the central spots $c\,c'$, one on the nasal half and one on the temporal half, and therefore on corresponding points. The *horopteric vertical* of Müller passes through $A$ and perpendicular to the plane of the circle (i. e., of the diagram).

Fig. 73.



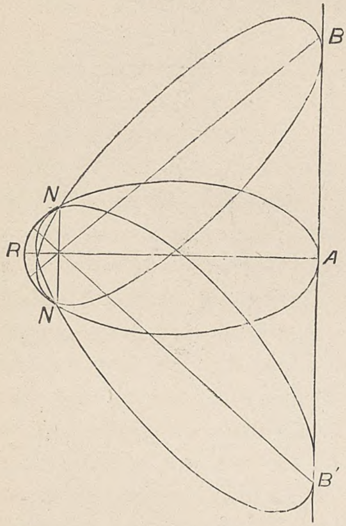

Horopteric Circle of Müller.

Claparède * makes the horopter a surface, of such a form that it contains a straight line passing through the point of sight and perpendicular to the visual plane, and

* "Archives des Sciences," 1858, vol. iii, p. 161.

also such that every plane passing through the optic centers makes by intersection with this surface the circumference of a circle. In other words, he thinks that the horopter is a surface which contains the *horopteric vertical* $B\,A\,B'$, Fig. 74, and the horopteric circle, $N\,A\,N'$, and in addition is further characterized by the fact that the intersection with it of every plane passing through the optic centers $N\,N'$ upward as $N\,B\,N'$, or downward as $N\,B'\,N'$ is also a circle. It is evident that, as these circles increase in size upward and downward, the horopter according to Claparède is a surface of singular and complex form.

FIG. 74.




HOROPTER ACCORDING TO CLAPARÈDE.

Helmholtz arrives at results entirely different. According to him, the horopter varies according to the position of the point of sight, and is therefore very complex. He sums up his conclusions thus: *

"1. Generally the horopter is a line of double curvature produced by the intersection of two hyperboloids, which in some exceptional cases may be changed into a combination of two plane curves.

"2. For example, where the point of convergence

* Croonian Lecture, in "Proceedings of the Royal Society," xiii (1864), p. 197; also "Optique Physiologique," p. 901 *et seq.*

(point of sight) is situated in the median plane of the head, the horopter is composed of a straight line drawn through the point of convergence, and a *conic section* going through the optic centers and intersecting the straight line.

"3. When the point of convergence is situated in the plane which contains the primary directions of both visual lines (primary visual plane), the horopter is composed of a *circle* going through that point and through the optic centers (horopteric circle), and a straight line intersecting the circle.

"4. When the point of convergence is situated both in the middle plane of the head and in the primary visual plane, the horopter is composed of the horopteric circle and of a straight line going through that point.

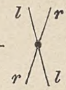
"5. There is only one case in which the horopter is a *plane*, namely: when the point of convergence is situated in the middle plane of the head and at an infinite distance. Then the horopter is a plane parallel to the visual lines, and situated beneath them at a distance which is nearly as great as the distance of the feet of the observer from his eyes when he is standing. Therefore, when we look straight forward at a point on the horizon, the horopter is a horizontal plane going through our feet; *it is the ground on which we stand.*

"6. When we look not at an infinite distance, but at any point on the ground on which we stand which is equally distant from the two eyes, the horopter is not a plane, but the straight line which is one of its parts coincides with the ground."

Some attempts have been made to establish the existence of the horopteric circle of Müller by means of experiments. A plane is prepared and pierced with a multitude of holes into which pegs may be set. The

eyes look horizontally over the plane on one peg, and the others are arranged in such wise that they appear single. It is found that they must be arranged in a circle. I have tried repeatedly, but in vain, to verify this result. The difficulty is the extreme indistinctness of perception at any appreciable distance from the point of sight to one side or the other. But, as a general fact, the results reached by the observers thus far mentioned have been reached by the most refined mathematical calculations, based on certain premises concerning the position of corresponding points and on the laws of ocular motion. We will examine only those of Helmholtz, as being the latest and most authoritative.

Helmholtz's results are based upon the law of Listing as governing all the motions of the eye, and upon his own peculiar views concerning the relation between what he calls the *apparent* and the *real* vertical meridian of the retina. According to him, the *real* vertical meridian of the eye is the line traced on the retina by the image of a really vertical linear object when the median plane of the head is vertical and the eye in the primary position. The *apparent* vertical meridian of the eye is the line traced by the image of an apparently vertical linear object in the same position of the eye. This is also called the *vertical line of demarkation*, because it divides the retina into two halves which correspond each to each and point for point. Now, according to Helmholtz, the *apparent* vertical meridian or vertical line of demarkation does not coincide with the *real* vertical meridian, but makes with it in each eye an angle of $1\frac{1}{4}°$, and therefore with one another in the two eyes of $2\frac{1}{2}°$. The horizontal meridians of the eyes, both real and apparent, coincide completely. Therefore, if the two eyes were brought together in such wise that their

*real* vertical and horizontal meridians should coincide, their *apparent* horizontal meridians would also coincide; but the apparent vertical meridians would cross each other at the central spot thus— 

, making an angle of $2\frac{1}{2}°$. For this reason a perfectly vertical line will appear to the right eye not vertical, but inclined to the left, and to the left eye inclined to the right. In order that a line shall appear perfectly vertical to one eye, it must incline for the right eye $1\frac{1}{4}°$ to the right, and for the left $1\frac{1}{4}°$ to the left. But a horizontal line appears truly horizontal. Therefore an upright rectangular cross will appear to the right eye thus— , and to the left eye thus— . The inclination of these lines is, however, exaggerated. If, therefore, according to Helmholtz, we make a diagram of which one half is composed of black lines on white ground, and the other of white lines on black ground, like those already used, but in which, while the horizontals run straight across horizontally, the verticals on the right half are inclined $1\frac{1}{4}°$ to the right, and on the left half the same amount to the left (Fig. 75), then, on combining these by gazing beyond the plane of the diagram (i. e., with parallel eyes), either with the naked eye or with the stereoscope, the verticals will be seen to come together parallel and unite perfectly.

Now Helmholtz's views of the form of the horopter are based wholly on this supposed relation of real and apparent vertical. Take for example his case of the eyes fixed on a distant point on the horizon. In this case, he says, "the horopter is the ground on which we stand." This is true if the relation above mentioned is

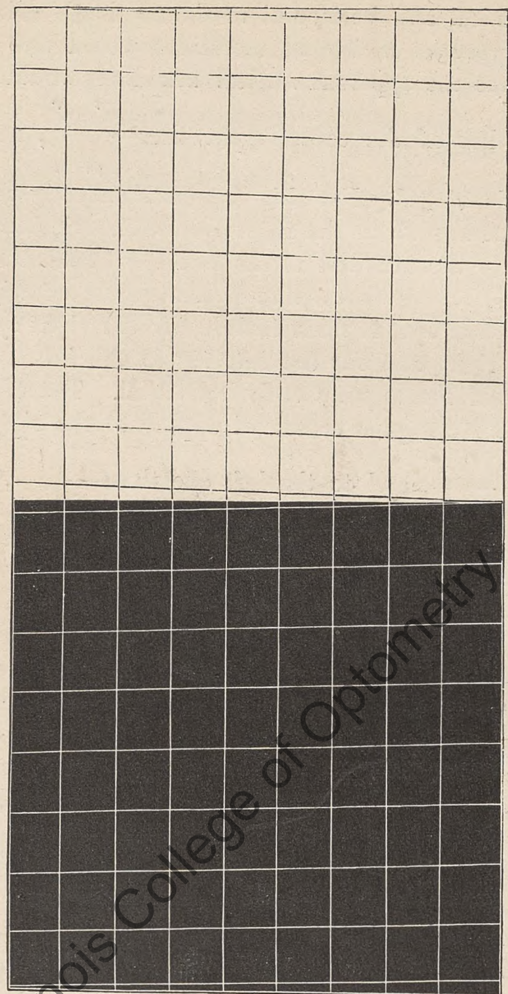


FIG. 75.

DIAGRAM SHOWING VERTICALS INCLINED $\frac{1}{4}$°. (Taken from Helmholtz.)

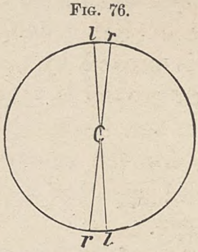
true; for, with an interocular distance of $2\frac{1}{2}$ inches, two lines drawn through the optic centers, each inclined $1\frac{1}{4}$° with the vertical and therefore $2\frac{1}{2}$° with each other,

would in fact meet about 5 feet below—i. e., about the feet. If, therefore, we place two actual rods together on the ground between the feet, and the upper ends before the pupils, the eyes being parallel, it is evident that the image of the right rod on the right retina and that of the left rod on the left retina would fall exactly on Helmholtz's apparent vertical meridian, and, if Helmholtz's views be correct, on the vertical lines of demarkation and on corresponding points of the retinæ, and thus would be binocularly combined and seen as a single line lying along the ground to infinite distance. And conversely, with the eyes parallel and the lines of demarkation inclined $1\frac{1}{4}°$ with the vertical, a rod lying on the ground to infinite distance would cast its images on these lines, and therefore be seen single throughout.

There are several curious questions which force themselves on our attention here if Helmholtz's view be true.

1. If we suppose the two eyes to be placed one on the other, so that the real vertical meridians coincide, we have already seen that Helmholtz's apparent verticals or lines of demarkation will cross each other like an X, as in Fig. 76, making with each other an angle of $2\frac{1}{2}°$. Now the two rods $2\frac{1}{2}$ inches apart at the height of the eyes, and meeting below at the feet, or the rod lying along the ground to infinite distance, would occupy with their images only the upper half of the X. But suppose the two rods, instead of stopping opposite the eyes, to continue upward to the limits of the field of view. Obviously this upper half would cast images on the lower half of the X, and therefore would be seen single also. Where shall we

Fig. 76.




The Retinæ superposed.—$r$ $r$, line of demarkation of right eye; $l$ $l$, line of demarkation of left eye.

refer them? Or, to express it differently, the horopter with the eyes looking at a distant horizon, according to Helmholtz, is the ground we stand on; but this is evidently pictured on the upper halves only of the two retinæ. Where is the other half of the horopter corresponding to the lower halves of the retinæ?

2. Again: According to Helmholtz, in looking at a distance the horopter is the ground we stand on, and he gives this as the reason why distance along the ground is more clearly perceived than in other positions.* On the contrary, it seems to me that it would have just the reverse effect. If the horopter were the ground we stand on, then relative distances on the ground could not be perceived by binocular perspective at all; for this is wholly dependent on the existence of double images, which could not occur in this case by the definition of the horopter. It would be therefore only by other forms of perspective that we could distinguish relative distance along the ground. But that we do perceive perspective of the ground binocularly—i. e., by double images—is proved by the fact that the perspective of the receding ground is very perfect in stereoscopic pictures, where the images of nearer points are necessarily double; for the camera has no such distinction between real and apparent verticality as Helmholtz attributes to the eye.

But it is useless to argue the point any further, for I am quite sure that the property which Helmholtz finds in his eye is not general, and therefore *not normal*. We have seen that in convergence the eyes rotate outward, so as to bring about the very condition of things temporarily which Helmholtz finds permanent in his eyes. I have therefore thought it possible, or

* *Op. cit.*, p. 923.

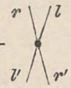
even probable, that the same habits in early life which, by constant adapting of the eyes to vision of near objects, finally produce myopy, may also, by constant slight rotation of the eyes outward and *distortion* * in convergence on near objects, finally bring about a permanent condition of slight distortion and outward rotation of $1\frac{1}{4}°$. Helmholtz is slightly myopic.†

However this may be, I am sure there is no such relation between real and apparent vertical meridian in my eyes as that spoken of by Helmholtz. All the experiments supposed to prove such relation fail completely with me. A vertical rectangular cross appears rectangular to either eye. The lines of Helmholtz's diagram, Fig. 75, when combined beyond the plane of the diagram, either by the naked eyes or by a stereoscope, do not come together parallel, but with a decided angle, viz., $2\frac{1}{2}°$. But when I turn the diagram upside down, and combine by squinting, then the vertical lines, being inclined the other way, as in my diagram, Fig. 68, combine perfectly by outward rotation of the eyes. I have constructed other diagrams with less and less inclination of the verticals, until the inclination was only 10′, and still I detected the want of parallelism when combined beyond the plane of the diagram. Beyond this limit I could not detect it, but I believe only because the limit of perception was passed; for when the lines are made perfectly vertical, they come together perfectly parallel and unite absolutely. It is certain, therefore, that in my eyes the vertical line of demarkation coincides completely with the true vertical meridian.

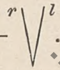
Meissner ‡ alone, of all writers with whom I am ac-

* Simple rotation is not sufficient, because this would affect also the horizontal meridian. † *Op. cit*, p. 914.

‡ Meissner, "Physiologie des Sehorgans"; also "Archives des Sciences," vol. iii (1858), p. 160.

quainted, attempts to determine the horopter directly by experiment. According to him, if a stretched thread be held in the median plane at right angles to the primary visual plane, about 6 to 8 inches distant, and the point of sight be directed on the middle, the thread will not appear single, but the two images will cross each other at the point of sight thus— 

, $r\ r'$ being the right-eye image, and $l\ l'$ the left-eye image. Now, as the images are heteronymous at the upper end and homonymous at the lower end, it is evident that they will unite at some farther point above and some nearer point below. By *inclining* the thread in the manner indicated—i. e., by carrying the upper end farther and bringing the lower end nearer—the two images come together more and more, until at a certain angle of inclination, varying with the distance of the point of sight, they unite perfectly. The thread is now in the horopter.

*Experiment.*—I find that the best way to succeed with Meissner's experiment is as follows: Hold a stretched black thread parallel with the surface of the glass of an open window, and within half an inch of it. Now, with the eyes in the primary position, look, not at the thread, but at some spot on the glass. It will be seen that the double images of the thread are not parallel, but make a small angle with each other, thus— 

. Now bring the lower end nearer the observer very gradually. It will be seen that the double images become more and more nearly parallel, until at a certain angle of inclination the parallelism is perfect. I have made several experiments with a view to measuring the angle of inclination for different dis-

tances of the point of sight. I find that for 8 inches the inclination is about 7° or 8°; for 4 inches, about 8° or 9°. It seems to increase as the point of sight is nearer. But of this increase subsequent experiments make me doubtful.

Meissner's results may be summarized thus:

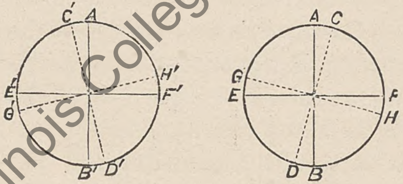
1. With the eyes in the primary position and the point of sight at infinite distance, the horopter is a plane perpendicular to the median line of sight (plane of Aguilonius).

2. For every nearer point of sight in the primary plane, the horopter is not a surface at all, but a *line* inclined to the visual plane and dipping toward the observer, the inclination increasing with the nearness of the point of sight or degree of convergence.

3. In turning the plane of vision *upward*, the inclination of the horopteric line increases. In turning the plane of vision *downward*, the inclination of the horopteric line decreases, until it becomes zero at 45°, and the horopteric line expands into a plane passing through the point of sight and perpendicular to the median visual line.

Furthermore, Meissner attributes these results to a rotation of the eyes on the optic or visual axes *outward*;

FIG. 77.




so that the vertical lines of demarkation, $C\ D$, $C'\ D'$, Fig. 77, no longer coincide perfectly with the vertical

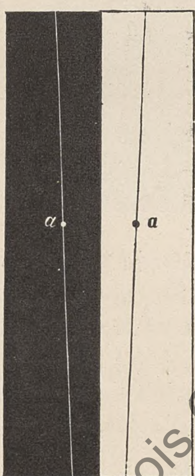
meridians $A\ B$, $A'\ B'$, nor the horizontal lines of demarkation $G\ H$, $G'\ H'$ with the horizontal meridians $E\ F$, $E'\ F'$, as they do when the eyes are parallel, but cross them at a small angle. With eyes parallel, the images of a vertical line will fall on the vertical lines of demarkation (for these then coincide with the vertical meridians) and be seen single. But if the eyes rotate outward in convergence, then the images of a vertical line will no longer fall on the vertical lines of demarkation, and therefore will be seen double except at the point of sight. In order that the image of a line shall fall on the vertical lines of demarkation and be seen single, with the eyes in this rotated condition, the line must not be vertical, but inclined with the upper end farther away and the lower end nearer to the observer. It is evident also that under these circumstances the horopter can not be a surface, but is *restricted to a line.* This requires some explanation.

If the eyes be converged on a vertical line, and then rotated on their optic axes, as we have seen, the line will be doubled except at the point of sight. This doubling is the result of *horizontal* displacement of the two images in opposite directions at the two ends—the upper ends heteronymously, the lower ends homonymously. Now, since heteronymous images unite by carrying the object farther away and homonymous images by bringing it nearer, it is evident that if the line be inclined by carrying the upper end farther and bringing the lower end nearer, the two images will unite completely, and thus form a horopteric line. But all points to the right or left of this horopteric line will also double by rotation of the eyes; but this doubling is by *vertical* displacement, as shown in Fig. 77. Now doubling by vertical displacement can not be remedied by increasing

or decreasing distance, *because the eyes are separated horizontally.* It is therefore irremediable. Hence no form of surface can satisfy the conditions of single vision right and left of the horopteric line. Hence, also, the restriction of the horopter to a line, and the inclination of that line on the plane of vision, are necessary consequences of the rotation of the eyes on their visual axes. This rotation I have already proved in the most conclusive manner by experiments detailed in the last chapter.

It will be seen by reference to the preceding chapter that my results coincide perfectly with those of Meissner, although I was ignorant of Meissner's researches when I commenced my experiments many years ago (1867). The end in view in the two cases, and also the methods used, were different. Meissner was investigating the question of the horopter, and outward rotation of the eyes was the logical inference from the position of the horopter discovered by him. I was investigating the laws of convergent motion, and the nature of the horopter was a logical consequence of the outward rotation which I discovered. Meissner's method is, however, far less refined and exact than mine.

Fig. 78.

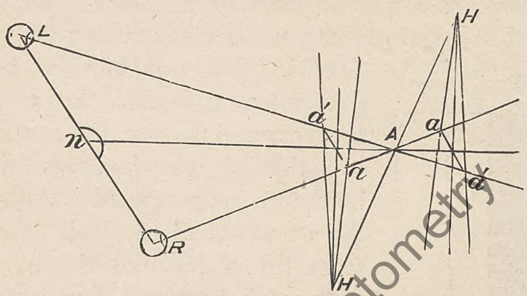



I have also proved the inclination of the horopteric line by direct experiments by my method.

*Experiment 1.*—If two lines, one black on white and the other white on black, be drawn with an inclination of $1\frac{1}{4}°$ with the vertical, and therefore $2\frac{1}{2}°$

with each other, and the eyes be brought so near to any points *a a*, Fig. 78 (taking care that the visual plane shall be perpendicular to the plane of the diagram), that these shall unite *beyond* the plane of the diagram at the distance of 7 inches, the two lines will coincide perfectly. If then the diagram be turned upside down, and the lines be again united by *squinting*—the diagram being in this case a little farther off, so that the point of sight shall again be 7 inches—the coincidence of the lines will be again perfect. Fig. 79—in which *R* and *L* represent the right and left eyes respectively,

FIG. 79.




*R L*, the two eyes; *n*, the nose; *A*, point of sight; *H H*, the horopteric line.

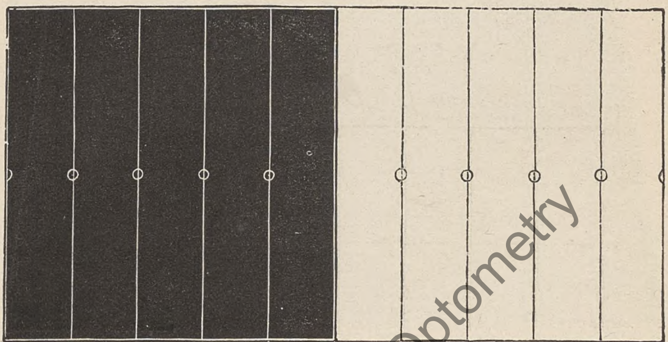
*a H* and *a′ H* the lines to be combined in these two positions, and *A* the point of sight—will explain how the combination takes place. The line *H A H* is the horopteric line.

This experiment is difficult to make, but I am quite confident of the reliability of the results reached. I made many experiments with different degrees of inclination of the lines *a H*, *a′ H*, and therefore with different degrees of convergence, and many calculations based on these experiments, to determine the inclination of the horopteric line for different degrees of conver-

gence. But the experiments are so difficult that, while in every case the inclination of the horopteric line was proved, the exact angle could not be made out with certainty. It seemed to me about 7° for all degrees of convergence, and therefore for all distances. It certainly does *not* seem to increase with the degree of convergence, as maintained by Meissner.

*Experiment 2.*—I next adopted another and I think a better method. I used a plane and diagram covered with true verticals only, as in Fig. 80. I placed this,

FIG. 80.

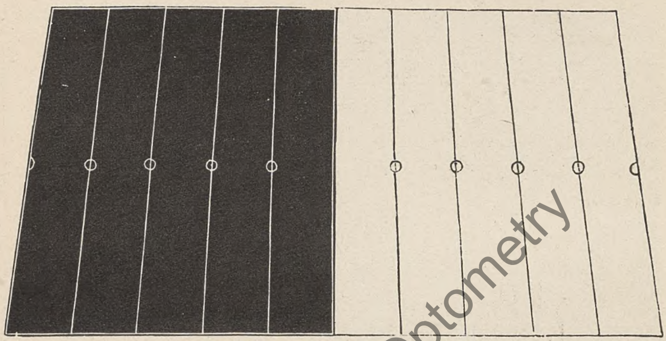


instead of vertical as in previous experiments, inclined 7° with the vertical, and therefore in the supposed position of the horopter. Placing the face in a vertical position and the plane of vision horizontal—i. e., my eyes at the same height as the little circles—I combined these successively, and watched how the lines came together. I found that when the plane is inclined 7° all the lines, even the farthest apart—viz., 30 inches—came together perfectly parallel. I then tried the plane inclined 8°; the parallelism was still complete for all degrees of convergence. But when the plane was inclined 9°, the in-

clination of the lines in coming together successively was distinctly perceptible. I am sure, therefore, that the true inclination is about 7° or 8°.

Such are the phenomena; now for the interpretation. It will be observed that when the plane represented by the diagram Fig. 80 is inclined to the visual plane, all the vertical lines converge by perspective; the convergence increasing with the distance from the central line, as in Fig. 81, which represents such an inclined plane referred to a plane perpendicular to the visual plane.

FIG. 81.



PROJECTION OF PLANE INCLINED 8°.

By calculation and careful plotting, I find that at the distance of 15 inches the convergence of the first two lines, 6 inches apart, for a plane inclined 8°, is each about 1° 31′, or to each other 3° 2′; of the second pair, 12 inches apart, 3° 3′ each, or 6° 6′ to each other; of the third pair, 18 inches apart, 4° 35′ each, or 9° 10′ to each other; of the fourth pair, 24 inches apart, 6° 7′ each, or 12° 14′ to each other; of the fifth pair, 30 inches apart, 7° 40′ each, or 15° 20′ to each other. Therefore, an increasing rotation of the eyes outward is necessary to bring these together parallel. The distance of the point

of sight measured from the line joining the optic centers varied from $4\frac{1}{2}$ inches in the first to $1\frac{1}{4}$ inch in the last case; but the inclination of the horopteric line was the same in every case. This is probably the most accurate means of determining by direct experiment both the horopter and the degree of rotation of the eyes for every degree of convergence of the optic axes.

*Experiment 3.*—I next tried the same experiment with the visual plane depressed 45°, but yet perfectly horizontal—i. e., with the chin lifted. In this position, on combining the vertical lines, I find that they retain perfectly their natural perspective convergence. On decreasing the inclination of the diagram the perspective convergence becomes less and less, until when the plane of the diagram is vertical the lines come together again parallel for all degrees of convergence, as already found in the previous experiment. I conclude therefore that in turning the visual plane downward the inclination of the horopteric line becomes less and less, until when the visual plane is depressed 45° it becomes perpendicular to that plane, and at the same time *expands to a surface*, but not to a *plane* as Meissner supposes.

In turning the visual plane upward, I find, especially for high degrees of convergence, that I must incline the plane of the diagram more than 8° (viz., about 10°) in order that the lines shall come together parallel. From this I conclude a higher degree of rotation of the eyes and a higher inclination of the horopteric line.

The points on which I do not confirm Meissner are: 1. The increasing inclination of the horopteric line with increasing nearness of the point of sight. I make it constant. 2. I think it probable also that Meissner is wrong in supposing that the horopter, when the visual plane is depressed 45°, is a *plane*. It is certainly a *sur-*

*face*, but not a plane; for it is geometrically clear that points in a perpendicular *plane* to the right or left of the point of sight can not fall on corresponding points of the two retinæ (page 117). The horopter in this case is evidently a curved surface. I do not undertake to determine its nature by mathematical calculation, and the experimental investigation is unsatisfactory for the reason already given, viz., the extreme indistinctness of perception of points situated any considerable distance from the point of sight in any direction.

In regard to the horopter I consider the following points to be well established: *

1. As a necessary consequence of the outward rotation of the eyes in convergence, for all distances in the primary visual plane the horopter is a line inclined to the visual plane, the lower end nearer the observer. But whether the inclination is constant, or increases or decreases with distance. I have not been able to determine with certainty. It is probably constant.

2. In depressing the visual plane, the inclination of the horopteric line becomes less and less, until when the visual plane is inclined 45° below the primary position the horopteric line becomes perpendicular to the visual plane, and at the same time expands into a surface. The exact nature of that surface I have not attempted to investigate, for reasons already explained; but it is evidently a curved surface.

3. In elevating the visual plane, especially with strong convergence, the inclination of the horopteric line increases.

Finally, the question naturally occurs: Of what advantage is this outward rotation of the eyes, and the

* Perhaps I ought to say in my own case and in those of several other persons with normal eyes.

consequent limitation of the horopter to a line? Or is it not rather a defect? Should the law of Listing be regarded as the ideal of ocular motion under all circumstances, and should the departure from this law in the case of convergence be regarded as abnormal? Or is there some useful purpose subserved by the rotation of the eyes on their optic axes? I feel quite sure that there is a useful purpose subserved; for there are special muscles adapted to produce this rotation, and the action of these muscles is consensual with the adjustments, axial and focal, and with the contraction of the pupil. This purpose I explain as follows:

A general view of objects in a wide field is a necessary condition of animal life in its higher phases; but an equal distinctness of all objects in this field would be fatal to that *thoughtful attention* which is necessary to the development of the higher faculties of the human mind. Therefore the human eye is so constructed and moved as to restrict as much as possible the conditions both of *distinct* vision and of *single* vision. Thus, as in *monocular* vision the more elaborate structure of the central spot restricts distinct vision to the visual line, and focal adjustment still further restricts it to a single point in that line, the point of sight, so also in *binocular* vision axial adjustment restricts single vision to the horopter, while rotation on the optic axes restricts the horopter to a single line.

# CHAPTER III.

## *ON SOME PECULIARITIES OF PHANTOM PLANES.*

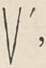
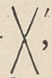
We have already shown how the figures of a regularly figured plane, like a tessellated pavement or a regularly patterned carpet or papered wall, may be combined either by crossing the eyes or (if the figures be not too large) by looking beyond the plane of the figures, as in the stereoscope, so as to make phantoms, which are nearer or farther off, and the figures smaller or larger than reality, according to the degree of ocular convergence, and therefore the apparent distance of the phantom. In Fig. 48, page 134, we have represented these phantoms as *planes parallel to the real plane;* but if closely observed they are seen to be neither perfect planes nor parallel to the real plane. The phenomena now about to be described have, some of them, not been heretofore noticed, and none of them have been satisfactorily explained.

### *1. The Phantom Plane not parallel to the Real Plane.*

*Experiment 1.*—I sit in a chair in the middle of a tessellated floor and direct the eyes on the floor at an angle of 45°. By ocular convergence I now combine successively the figures of the floor, stopping a little at each combination until the phantom image clears.

These phantom floors are distinctly perceived to be not horizontal, as they ought to be by geometric construction, but inclined, dipping away from the observer at higher and higher angle, as by greater convergence the phantom floor comes nearer and nearer. I am sure that by extreme convergence I can make the phantom slope at an angle of 30°–40°.

In addition to the slope of the plane, and closely connected therewith, another phenomenon is perceived. The figures change their shape, becoming elongated in the direction of the slope and in proportion to the angle of the slope. If, for example, the figures are regular squares, looked at in the direction of their diagonals they become greatly elongated rhombs, or if circles they become long ellipses.

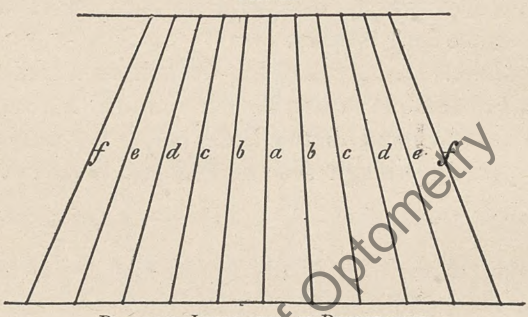
*Explanation. Principles.*—We have already seen (pages 140 and 141) that a slender rod held horizontally in the median plane, but a little below the horizontal plane passing through the two eyes and looked at with both eyes, is seen thus—, or thus—, or thus—, according as we look at the nearer end or the farther end or the middle point. In this case—i. e., when the rod is horizontal—the angle between the two images is small.

If now the nearer end of the rod be lifted so as to bring it nearly in coincidence with the plane of sight, the angle between the images will become greater, but the vertical length of the projection less, until when the rod is *in* the plane of sight, the angle becomes 180° and the two images are in the same horizontal straight line. Of course, to the *binocular observer* it does not seem like a horizontal straight line, because *he* introduces the element of depth of space by binocular per-

spective. To *him* it would look like a V or an X looked at *end on.*

*Application of Principles in Explanation of the Slope.*—The figures of a tessellated plane of course lie in *parallel lines.* We will suppose these lines to run from the observer. By geometric or monocular perspective such lines converge to a vanishing point on the horizon. Leaving out the figures of the pattern, Fig. 82 represents the projection of such parallels as seen *with one eye.* As seen with two eyes, of course, there are *two* images of all these lines crossing one another at small angle, as shown above. Let us fix the mind on the

FIG. 82.




PARALLEL LINES SEEN IN PERSPECTIVE.

middle one, *a*, alone. In natural vision its two images would cross at small angle at the point of sight. But in making the phantom plane, *b b* or *c c* or *d d* or *e e*, etc., are brought together in the middle, combined and viewed *as the middle line.* But it is evident that the angle of perspective convergence, and therefore the angle of crossing one another when they come together, is greater and greater, as by greater convergence they are brought from greater distance right and left. In other words, the *perspective angle is added to the binoc-*

*ular angle and all is credited to the binocular angle, be cause viewed as a middle line which ought not to have any perspective angle at all.* But we have already seen that the crossing of binocular images of lines at higher angle means a nearer approach to the plane of sight —a looking more *end on.* In other words, it means a lifting of the nearer end of the plane. Therefore as more and more separated lines of figures, *b b*, *c c*, *d d*, *e e*, etc., are brought forward and united in front, and the angle of crossing of the lines becomes greater, the slope of the phantom plane becomes greater, until, if we could bring together lines from an infinite distance, the phantom plane would coincide with the plane of sight—i. e., would slope 45°.

*Elongation of the Figures.*—This follows as an obvious and necessary consequence of the slope. For since the angle subtended by the plane at the eye, or the retinal image, remains the same, the length of the plane and all its figures must seem greater in proportion to the degree of slope, precisely as shadows cast on a plane are longer in proportion as the angle of the light to the plane becomes less.

*Experiment 2.*—In experimenting with the floor, the observer's body prevents viewing the phantom in the contrary direction. Therefore we take next a vertical wall, such as a regularly patterned wall-papering or a coarse wire-netting. The windows of the basement of one of the university buildings are protected by a coarse wire-netting with lozenge-shaped meshes about $2\frac{1}{2}$ inches in their shorter or horizontal diameter. Standing before this and combining by extreme convergence, on looking upward the phantom slopes *away* upward; looking downward, it slopes *away* downward. So that sweeping the plane of sight upward and down-

ward alternately the phantom plane seems to dip away up and down from an anticline, or arch. The explanation of this is, of course, the same as that already given in the case of the floor.

By careful experiment it is found that the top of the arch is not on a level with the eyes, but a *little above*, making with the horizontal an angle of about 7°. This is the result of the rotation of the eyes on the visual axes in convergence, already demonstrated on pages 199–212, and is a beautiful proof of such rotation.

### 2. *The Phantom not a Plane.*

*Experiment 3.*—Instead of looking obliquely on the experimental plane we next look perpendicularly on it, or, more accurately, 7° inclined upward. By extreme convergence in this position the phantom plane is seen to slope away on *either side* so as to form a sort of saddle. Similarly, on looking upward or downward, the sloping plane is not a perfect plane, but bulged a little along the middle line. Sweeping the point of sight about in all directions, all these effects are combined and the phantom surface slopes away in all directions, forming a mound.

*Explanation of the Transverse Arching.*—It will be remembered that impressions on non-corresponding points produce double images; moreover, that when the non-corresponding points are *nearer together* than corresponding points or central spots, the double images are homonymous, and when farther apart than central spots they are heteronymous; and still further, that homonymously double images mean that the object which produces them is *farther away* than the point of sight, while heteronymously double images indicate

that the object producing them is *nearer* than the point of sight. We are now prepared to explain.

In the diagram (Fig. 83) *P P* is the experimental plane, *R* and *L* represent a portion of the retinæ of the two eyes, of which *n n′* are the nodal points. The eyes are supposed by convergence to be fixed on the points *b b′*, which impressing corresponding points—viz., central

FIG. 83.

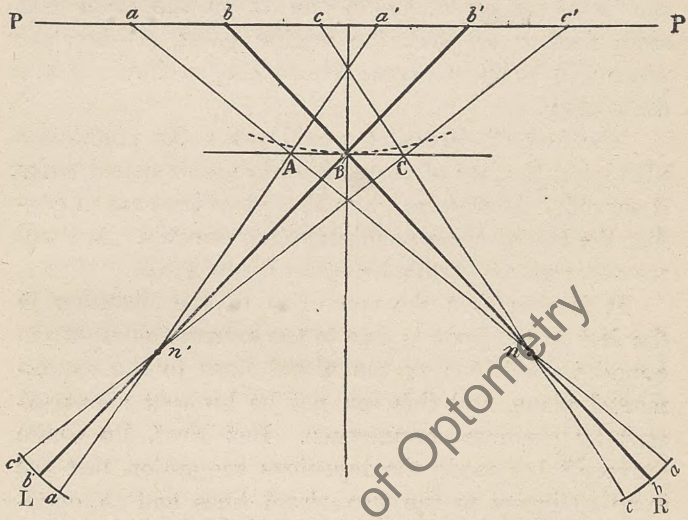



DIAGRAM SHOWING THE CAUSE OF THE TRANSVERSE ARCHING OF THE PHANTOM PLANE.

spot *b b′*—will be united and seen *single* at point of sight, *B*. At the same time the points *a a′* and *c c′* of the plane would also combine by *geometric construction* and be seen at *A* and *C*, as a phantom plane parallel to the experimental plane. Such would be the case by geometric construction and by the *law of direction*. And such would be the case also by the law of corresponding points *if the retinæ were planes parallel to the experi-*

*mental planes.* But the retinæ are concaves at right angles to the lines of sight *b n b*, *b′ n′ b′*. It is evident, therefore, that, taking the retinal points *b′ b* (central spots) as corresponding points, *a a* and *c c* are not exactly corresponding points. They are *nearer together* than corresponding points, and therefore the objects which produced them will seem farther off than the point of sight. Therefore in the phantom surface the point *A* on one side and *C* on the other will seem farther off than the middle point, *B*—i.e., the plane will be arched from side to side, as shown by the dotted line.

The law of direction would make the phantom a plane, but the law of corresponding points would make it curved. Therefore, when these two laws are in conflict the law of corresponding points prevails. We will see other proofs of this hereafter (page 293).

It is seen that the convexity of the phantom in the last experiment is due to the extreme obliquity in opposite directions of the visual lines to the experimental plane, and this can not be brought about except by extreme convergence. But Prof. Le Conte Stevens* has made the ingenious suggestion that the same obliquity to the two visual lines and in opposite directions may be easily effected, and the same result in the phantom produced by dividing the experimental plane along the middle and bending the two halves in opposite directions. This method has the great advantage of allowing combination *beyond* the plane of the object also. But although the result is similar, viz., a curved phantom, yet the phenomena and the explanation are different, as we now proceed to show.

* Philosophical Magazine, May, 1882, p. 314.

*Experiment 4.*—In the diagram Fig. 84 $a\ e\ a'\ e'$ are the regularly figured experimental planes inclined to each about 90°. $R$ and $L$ are the positions of the two eyes. If now the right eye be directed on the middle point, $c$, of the right plane, and the left on the middle point, $c'$, of the left plane, these will combine and be seen single at $C$. At the same time, by *geometric construction*, all the other figures of the two planes will be seen as $A, B, D, E$, showing a strongly convexly curved phantom, $A, B, C, D, E$. If, on the contrary, the figures $c\ c'$ be combined by *convergence*, a *concave* surface is developed by geometric construction. It is evident, however, as already said, that the explanation in this case is at least partly different, for the curvature of the phantom is brought out by geometric construction alone, although it is probably increased by the property of corresponding points.

Fig. 84.

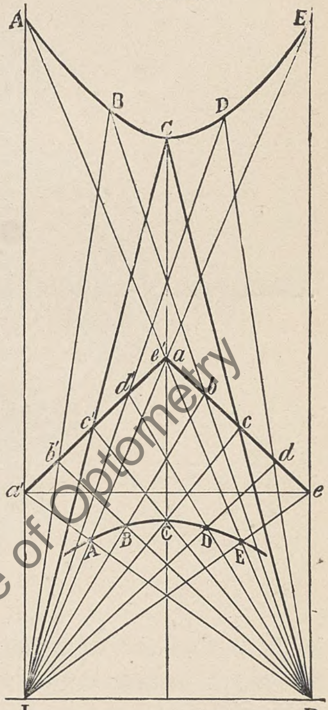


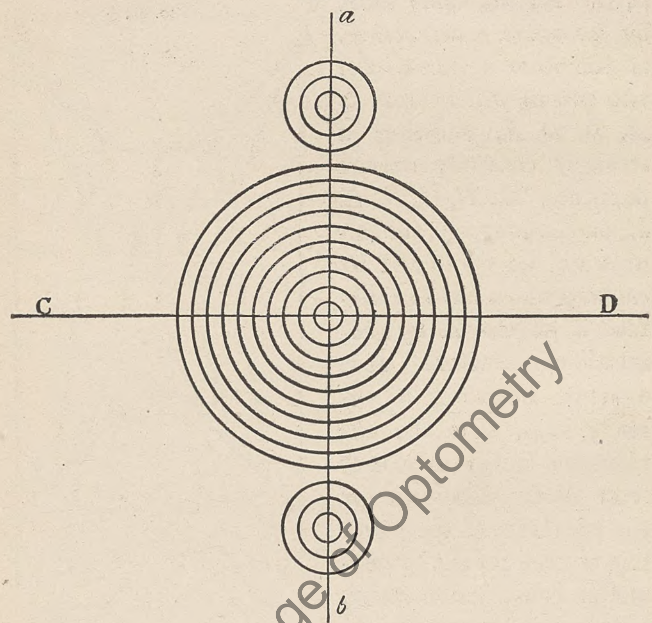

Diagram showing Explanation of Prof. Stevens's Phenomenon.

*Experiment 5.*—We are indebted to Prof. Stevens* for the discovery and explanation of another very striking and beautiful phenomenon.

* Philosophical Magazine, May, 1882, p. 315.

Let a similar series of concentric circles be drawn on the two halves of a stereoscopic card, *partly* cut through along the middle line, so that the card may be bent either way at any angle. I have placed the two series of concentric circles on opposite pages of the

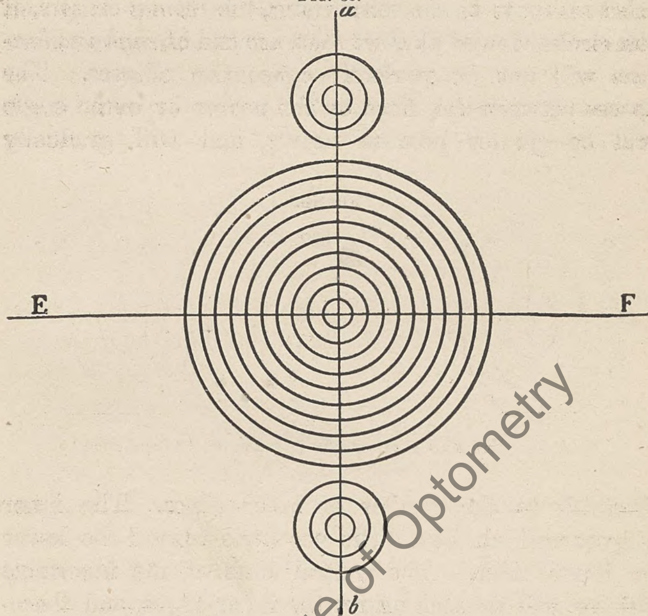
Fig. 85.




book so that the experiment may be made by placing the pages at any angle with one another (Fig. 85). Now if, lying flat, the circles be combined by convergence with the naked eye, or without convergence with the stereoscope, the combined phantom is sensibly flat. But if the card be bent along the middle line toward the observer (book partly closed) so as to make an angle of 90° or less with one another, and then the cir-

cles be combined by convergence, the phantom becomes a most beautiful elliptic *concave* or *elliptic saucer*. By varying the angle between the two planes, it is seen that both the ellipticity and the concavity increases as the angle is less. For best effect the line of intersec-

Fig. 85.




tion of the planes (back of the book) must be at right angles to the visual plane, so that the lines $C$, $D$, $E$, $F$ coincide perfectly, and also the planes must be *equally inclined* to the median plane of sight. We will call this the *normal position* of the plane.

If, next, the planes be inclined the other way—i. e., away from the observer, by bending the book backward—then by combination the phantom becomes a

beautiful *convex ellipse*, or elliptic saucer viewed from the under side. Of course these effects are exactly reversed if the combination is made beyond the object, either by the naked eyes or by means of a stereoscope.

*Explanation.*—It is evident that the *projections*, or, what amounts to the same thing, the *retinal images*, of the circles viewed at *short distance* and at *high inclination* will not be perfectly concentric ellipses. The spaces between the lines on the nearer or outer edges will be greater because nearer, and will gradually

FIG. 86.


DIAGRAM SHOWING CAUSE OF THE CONCAVITY. (After Stevens.)

diminish to the farther or inner edges. The inner ellipses will all be a little eccentric toward the lower or inner sides. The central dots of the innermost ellipses will be each nearer the inner edges, and therefore nearer together than the centers of the outer ellipses. Now, by reference to Figs. 52 and 56, pages 148 and 152, it will be seen that these are exactly the conditions for making a concave phantom by convergence and a convex one by use of stereoscope. In Fig. 86 (taken from Stevens) we give a simplified representation of the appearance of concentric circles viewed obliquely at short distance. If these be united by convergence, the phantom is seen to be deeply concave—

far too deeply, because the eccentricity is greatly exaggerated. This is a complete explanation of the concavity *from side to side.*

*Experiment 6.*—But to complete the explanation, especially of the fore and aft curvature of the phantom saucer, one more experiment is necessary.

It will be observed in the last experiment (5) that with the cards (Fig. 85) in the normal position the phantom saucer lies level, with only its lowest point touching the line *a b*. If now we tip the cards one way or the other so as to make them inclined to the visual plane, but without altering their mutual relation, the phantom saucer is seen to tip *in the contrary way* and to a much *greater degree.* Thus, when the lower side of the cards is *lifted up* the corresponding edge of the saucer goes *down*, first *to*, and then below the line *a b*, more and more, until when the cards are tipped 25° to 30° the line *a b* pierces the center of the saucer at right angles. At the same time, the lines *C, D, E, F*, which in the normal position are coincident, are seen to cross one another at the center of the saucer at an angle of 25° to 30°. If the cards be tipped in the other direction—i. e., the upper end be lifted—then the *lower* edge of the saucer is lifted correspondingly, but in much greater degree, until it again becomes at right angles to the line *a b*. It is truly wonderful how sensitive the phantom is to movements of the planes. Such are the facts. Now the explanation.

*Explanation.*—When the planes are in the normal position, the major axes of the uncombined ellipses are nearly vertical to the visual plane—they are really slightly curved (see Fig. 86)—but as soon as the planes are tipped so as to be inclined to the visual plane these major axes become inclined to the vertical lines

*a b*, *a b* in opposite directions, so that their upper ends are farther apart than their lower ends. In combining them by convergence it will require more convergence to combine the upper ends, and this end will therefore, in the resulting phantom, seem nearer than the lower end. Fig. 87 is a simplified representation of the position of the two ellipses. If these be combined by convergence it is seen at once that the resulting phantom

FIG. 87.

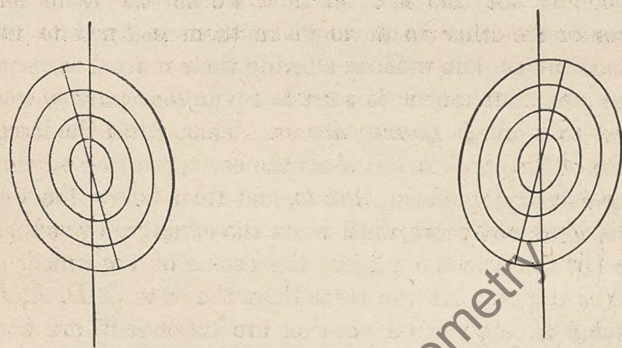


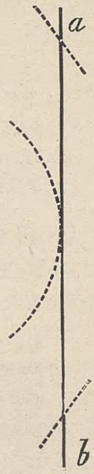
DIAGRAM TO SHOW THE CAUSE OF THE FORE AND AFT CURVATURE.

is strongly inclined with the upper edge nearer, and that the line *a b* pierces it in the center almost, if not quite, at right angles. Returning again to the phantom saucer of experiment 6, if we push the inclination of the cards still farther, the inclination of the long axes of the ellipses becomes too great to combine readily. We are plagued by a too obvious doubling of the images of the two ellipses; but the *cause* of the phenomenon of the tipping of the saucer—viz., the inclination of the two ellipses—becomes at once evident.

Now if we return to the fifth experiment, it becomes evident that the true cause of the fore and aft concavity

of the phantom saucer is to be found in this last experiment. The slightest inclination of the visual plane to the phantom plane causes a tipping in a contrary sense of the figures on the plane and to a much greater degree. Now the visual plane is at right angles only at the center of the saucer and is inclined in opposite directions above and below. Therefore the saucer is lifted both above and below, and is therefore concave fore and aft. This is implied in the figure of Prof. Stevens (Fig. 86) especially in the curved lines $A\ C\ B$, $A'\ C'\ B'$, but is not explicitly stated in his paper. The two smaller circles above and below are of course inclined in opposite directions, and have been added only to make this clear. The position of all the circles in the phantom when viewed in the normal position, as in experiment 5, is shown in section in Fig. 88. The line $a\ b$ touches the middle figure and pierces the other two.

Fig. 88.



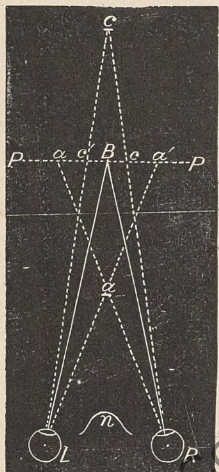

Section of Binocular Combination of Fig. 85.

# CHAPTER IV.

*ON SOME FUNDAMENTAL PHENOMENA OF BINOCULAR VISION USUALLY OVERLOOKED, AND ON A NEW MODE OF DIAGRAMMATIC REPRESENTATION FOUNDED THEREON.**

In all that I have said thus far, I have made use of the ordinary mode of representing binocular visual phenomena. I have done so because I could thus make myself more easily understood. But it is evident on a little reflection that the usual diagrams do not in any case represent the real *visual facts*—i. e., the facts as they really seem to the binocular observer.

Fig. 89.




Thus, for example, if $\underline{a}$, $B$, and $\underline{c}$, Fig. 89, be three objects in the median plane, but at different distances, and the two eyes, $R$ and $L$, be converged on $B$; as already explained, $\underline{a}$ and $\underline{c}$ will be both seen double—the former heteronymously, the latter homonymously. It will be observed that in the diagram the double images of both $\underline{a}$ and $\underline{c}$ are referred to the plane of sight $P\ P$. Now every one who has ever tried the experiment knows that the double images are not thus referred in natural

* This new mode was proposed by me in 1870.—Am. Jour., vol. i, p. 33. 1871. Some years afterward I learned that something of the same kind had been previously proposed by Hering.

vision; but, on the contrary, they are seen at their real distance, though not in their natural position. Indeed, it is only by virtue of this fact that we have perception of binocular perspective. The diagram therefore, although it truly represents the parallactic position of the double images, does not represent truly their apparent distance. If, on the other hand, we attempt in the diagram to refer the double images to their real distance (observing the law of direction), then they unite and form one, which is equally untrue. Thus, if we represent truly the visual position, we misrepresent the visual distance; if, on the contrary, we try to represent the visual distance, we misrepresent the visual position. It is evident therefore that the usual diagrams, while they represent truly many important visual phenomena, wholly fail to represent truly many others, especially the facts of binocular perspective.

The falseness of the usual mode of representation becomes much more conspicuous if, instead of two or more objects, we substitute a continuous rod or line. In this case the absurdity of projecting the double images on the plane of sight is so evident that it is never attempted. The mode universally used for representing the visual result when a rod is placed in the median plane is shown in Figs. 90–93, of which Fig. 90 represents the actual position of the rod in the median plane, and the actual position of the visual lines when the eyes are fixed on the nearer end *A*; Fig. 91, the same when the eyes are fixed on the farther end *B*; and Figs. 92 and 93, the visual results in the two cases respectively. Now it will be observed that in both these figures representing visual results (Figs. 92 and 93) the image of the rod belonging to each eye is coincident with the visual line of the other eye, and therefore

makes an angle with its own visual line equal to the visual angle $R\,A\,L$, $R\,B\,L$. But this is not true; for Figs. 90 and 91 show that it ought to make but half

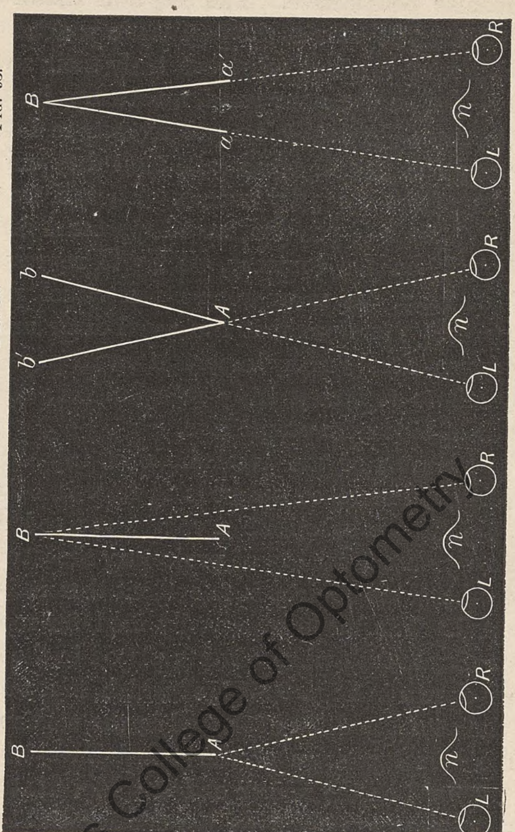



FIG. 90. FIG. 91. FIG. 92. FIG. 93.

that angle. If these figures therefore truly represent the position of the double images (as indeed they do), then they do not truly represent the position of the *visual lines.* The truth is, in natural vision *the visual*

*lines are shifted*, as well as the images of all objects not situated at the point of sight, and to the same degree, *so that the position of such objects relative to the visual lines is perfectly maintained in the visual result.*

It is evident then that figures constructed on the usual plan, while they give correctly the place and distance of objects seen single, fail utterly to give the place of double images. They are well adapted to express binocular combination of similar objects or similar figures on the plane of sight, but are wholly inadequate to the expression of the facts of binocular perspective, whether in natural objects or scenes or in stereoscopic pictures.

In an article published in January, 1871,* I proposed, therefore, a new and I am convinced a far truer mode of diagrammatic representation of the phenomena of binocular vision, applicable alike to all cases. I am satisfied that if this method had always been used, much of the confusion and many of the mistakes to be found in the writings on binocular vision would have been avoided. But it is evident that such a new and truer method must be founded upon some fundamental binocular phenomena usually overlooked. I must first therefore enforce these. They may be compendiously stated in the form of *two fundamental laws.* It will be best, however, before formulating them, to give some familiar experiments, and then to give the laws as an induction from the facts thus brought out.

*Experiment 1.*—If a single object, as for example a finger, be held before the eyes in the median plane, and the eyes be directed to a distant point so that their axes are parallel, the object will of course be seen double, the heteronymous images being separated from each

* "American Journal of Science," Series III, vol. i, p. 33.

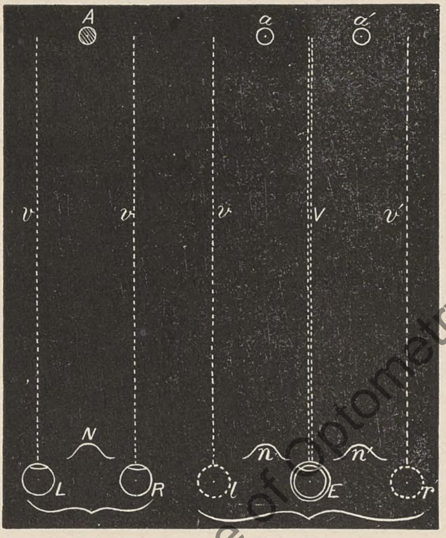
other by a space *exactly equal to the interocular space.* Now, *the nose is no exception to this law.* The nose is always seen double and bounding the common field of view on either side.

*Experiment 2.*—If two similar objects be placed before the eyes in the horizontal plane of sight, and separated by a space exactly equal to the interocular space, and the eyes be directed to a distant point so that their axes are parallel and the two visual lines shall pass through the two objects, then both objects will be doubled, the double images of each being separated by an interocular space; and therefore two of the four images—viz., the right-eye image of the right object, and the left-eye image of the left object—will combine to form a *single binocular image in the middle;* while the right-eye image of the left object will be seen to the left, and the left-eye image of the right object to the right. Thus there will be three images seen—a middle binocular image, and two monocular images, one on each side, that on the right side belonging to the left eye alone, and that on the left to the right eye alone. Now, *the eyes themselves are no exception to this law.* In binocular vision the eyes themselves seem each to double—two of the images combining to form *a binocular eye in the middle* (*œil cyclopienne*), while the other two are beyond the two images of the nose on either side, and therefore hidden from view. Each eye seems to itself to occupy a central position, while it sees (or would see if the nose were not in the way) its fellow on the other side of the double images of the nose.

In other words, in binocular vision, when the optic axes are parallel, as in gazing on a distant object, the *whole field of view, with all its objects, including the parts of the face, is shifted by the right eye a half in-*

*terocular space to the left, and by the left eye a half interocular space to the right, without altering the relative position of parts.* It is evident that, by this shifting in opposite directions, the two eyes with their visual lines are brought together in perfect coincidence, so that corresponding points in the two retinæ seem to be perfectly united.

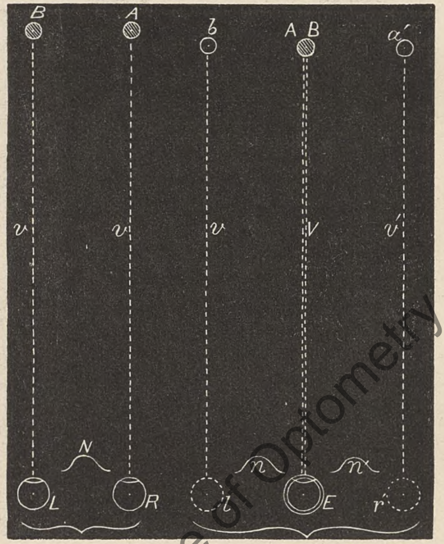
FIG. 94. FIG. 95.




The facts as thus far stated—both the *actual condition of things* as we *know* them, and the *visual results* as they *seem* to the binocular observer—are represented in the following diagrams. Fig. 94 shows the actual condition of things, and Fig. 95 the visual result, in the first experiment; Fig. 96 the actual condition of things, and Fig. 97 the binocular visual result, in the second experiment. To explain further: In Fig. 94, *R* and *L* are the right and left eyes; *N*, the nose; *A*, the object

in the median plane; the dotted lines $v$ $v$, the direction of the visual lines. Fig. 95 represents the visual results; $E$ being the combined or binocular eye (*œil cyclopienne*); $n$ and $n'$, the two images of the nose belonging to the right and left eyes respectively; $V$, the combined or binocular visual line, looking between the double images $a$ and $a'$ of the object $A$; while $r'$ is the position

FIG. 96. FIG. 97.

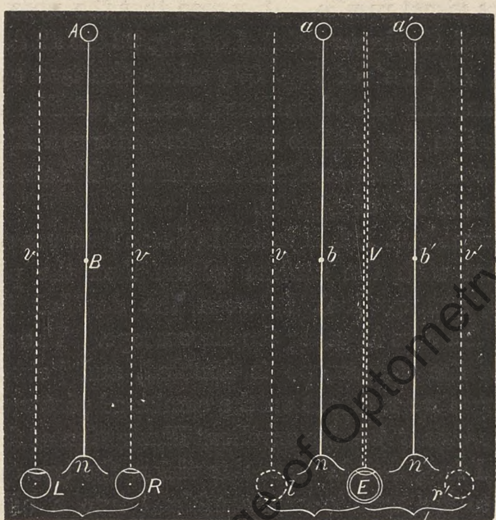



of the right eye as it would be seen by the left eye, and $l$ of the left eye as it would be seen by the right, if the nose were not in the way, and $v$ and $v'$ are the positions of their visual lines if they were visible lines. Fig. 96 represents the actual condition of things when two similar objects $A$ and $B$ are before the eyes in the visual lines $v$ $v$; and Fig. 97 is the visual result, in which $a'$ and $b$ are the monocular images, one belonging to the left and the other to the right eye, $AB$ the combined

or binocular image, and the other letters representing the same as before.

*Experiment 3.*—These facts are brought out still more clearly if, instead of an object like *A*, Fig. 94, we use a continuous line or rod, as in Fig. 90, page 250. We have seen above that, with the optic axes parallel, any object placed in the median line of sight, at whatever distance, is separated into two images an interocular

Fig. 98. Fig. 99.




space apart. Evidently, therefore, *the median line of sight itself is doubled*, and becomes two lines, which, resting on the nose on each side, run out parallel to each other indefinitely. Between these two lines the binocular eye (combined eyes) looks out along the combined visual line at a distant object. If the median *line* be occupied by a *real* visible line or a rod, we shall see two parallel lines or rods. If the median *plane* be

occupied by a *real* plane, we shall see two parallel planes bounding the binocular field of view on each side, between which we look.

These facts are represented by the diagrams Figs. 98 and 99. In Fig. 98, *B* represents a rod resting on the root of the nose *n*, and held in place by the point of the finger *A*; *R* and *L* are the two eyes, and *v* and *v* the two visual lines in a parallel position. Such is the actual condition of things. Now Fig. 99 represents the visual results. It is seen that the nose *n*, the rod *B*, and the finger-point *A* of Fig. 98 are all doubled, as *n n′*, *b b′*, *a a′* of Fig. 99; while the two eyes, *R* and *L*, and the two visual lines, *v* and *v*, of Fig. 98, are combined in the middle as the binocular eye *E*, which looks out along the combined visual line *V* between the parallel rods *b b′* of Fig. 99.

As already stated, if instead of a rod we use a plane coincident with the median plane, then the plane is doubled, and we look between the doubled images. This is the case in using the stereoscope. The median plane of the stereoscope is doubled, and between its two images we look out on the combined pictures.

*Experiment 4.*—An excellent illustration of the fundamental fact, that in binocular vision the two eyes are moved to the middle and combined into a binocular eye, must be familiar to every one who has ever worn spectacles. If the spectacles are properly chosen, so that the distance between the centers of the two glasses is exactly equal to the interocular space, then we see but *one* glass exactly in the middle, through which the binocular eye seems to look. We would see two other glasses, monocular images, right and left, if these were not hidden by the nose. We do indeed see two others in these positions if we remove the spectacles to such

distance that the nose no longer conceals them, while we still look through the middle glass at a distant object.

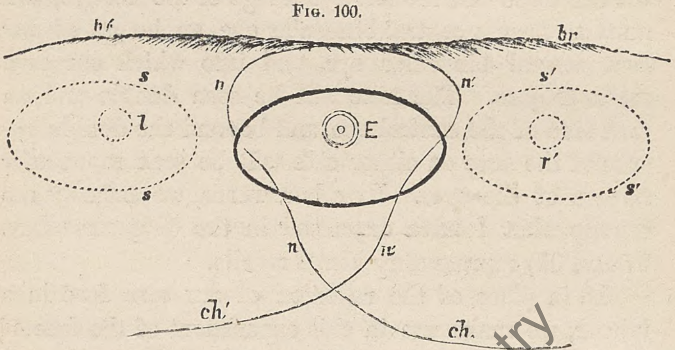
Many other familiar illustrations may be given. If we put our face against a mirror, so that forehead and nose shall touch the glass, and then gaze on vacancy, there will be of course four images of the two eyes in the mirror. Two of these, viz., the right-eye image of the right eye and the left-eye image of the left eye, will unite to form a central binocular eye, an image of our own central binocular eye, and into which our own seems to gaze. The nose will be seen double and on each side of the central eye, and beyond the double images of the nose on either side will be seen monocular images of the eyes. In other words, we actually see exactly what I have expressed in the diagrams (Figs. 97 and 99) representing visual results.

If, in place of the reflexion of our *own* face in a mirror, we make use in this experiment of the face of another person, placing forehead against forehead, nose against nose, and the eyes exactly opposite each other, and gaze on vacancy, the same visual result will follow. Our own central binocular eye looks between our two noses into another central binocular eye, situated also between two noses. Other monocular eyes are seen beyond the noses, right and left.

The fields of view of the two eyes are bordered by the nose, the brows, and the cheeks. Its form therefore varies in different persons. It has no definite limit on the outside—i. e., if projected on a plain surface. I reproduce as Fig. 100 the diagram already used on page 106, representing rudely the general character of the field of view of the binocular observer. I have introduced the *œil cyclopienne* and the two monocular images of the eyes; and, in order to make it more comprehensible,

I have supposed the observer to wear glasses. In this diagram, *n n* is an outline of the nose, *br* of the brow, and *ch* of the cheek of the right-eye field; *br′*, *n′ n′*, and *ch′*, the outline of the left-eye field. The middle space where they overlap, bounded on each side by the outline of the nose *n n*, *n′ n′*, is the common or binocular field occupied by the central binocular eye *E*, sur-

Fig. 100.




Diagrammatic Outline of Fields of View of Right and Left Eyes and of the Common Field.

rounded by the single ellipse of the combined spectacle-glasses. I have also introduced in dotted outline the left eye *l* and the spectacle-rim *s s* as they would be seen by the right eye, and the right eye *r′* and spectacle-rim *s′ s′* as they would be seen by the left eye, if the nose were not in the way.

**First Law.**—We are now in position to formulate the first law. I would express it thus: *In binocular vision, with the optic axes parallel, as in looking at a distant object, the whole field of view and all objects in the field, including the visible parts of the face, are shifted by the right eye a half interocular space to the left, and by the left eye the same distance to the right, without altering the relative positions of parts; so that*

*the two eyes with their two visual lines seem to unite to form a single middle binocular eye, and a single middle visual line, along which the eye seems to look.* It follows that any line, rod, or plane in the median line, as also the nose itself, is doubled heteronymously, and becomes two lines, rods, or planes, parallel to each other, and separated by a space exactly equal to the interocular space. Between the two noses, and between the two parallel lines, rods, or planes, the binocular eye seems to look out along the middle visual line upon the distant object. Of course, by this shifting of the twofields in opposite directions, all objects in the field are similarly doubled.

Thus in binocular vision the two eyes seem *actually* to be brought together and superposed, and corresponding points of the two retinæ to coincide. The two eyes become actually one instrument. And conversely, this apparent combination of two eyes and their visual lines is a necessary consequence of the law of corresponding points. For images on corresponding points are seen single; all objects on the two visual lines must impress corresponding points, viz., the central spots; therefore the visual lines themselves, if they were visible lines, would be seen single. But where could they be seen single except in the middle? Therefore the two visual lines must combine to form a single middle visual line.

We will next give experiments leading up to the second law. For this purpose let us recur to the experiment with the rod represented by Fig. 98. We reproduce this as Fig. 101, only simplifying by leaving out, in the visual result (Fig. 102), the monocular visual line $v\,v'$ of Fig. 99, in order to compare with it the results of subsequent experiments. As already explained, if the rod $B$ be placed in the median plane with the nearer end resting on the nose-root $n$, and the farther

Fig. 101.

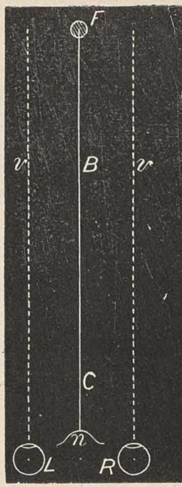
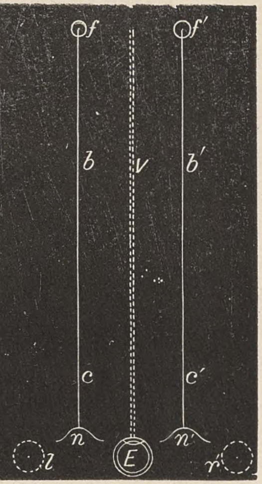



Fig. 102.




end held in place by the point of the finger $A$, the eyes looking at a distant object, as shown in Fig. 101, which represents the actual condition of things, then the rod,

Fig. 103.

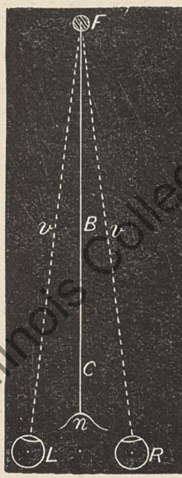
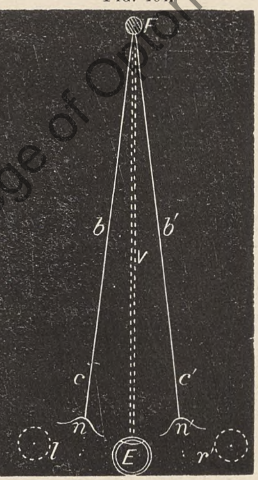


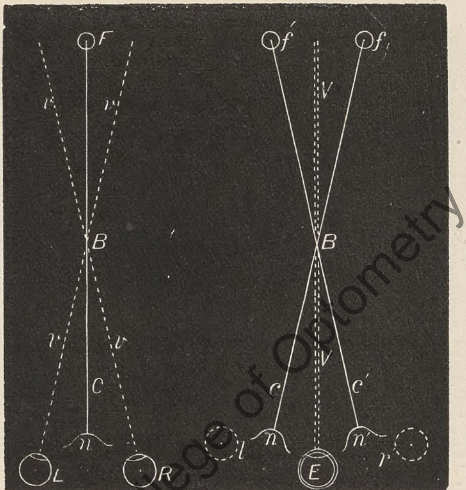

Fig. 104.



together with nose and finger-point, will be doubled heteronymously and become two parallel rods, between which the binocular eye will look out along the binocular visual line at the distant object, as shown in Fig. 102, which represents the visual results.

*Experiment 1.*—Now, while we hold the rod in the position represented by Fig. 101, instead of looking at a distant object with eyes parallel, let the eyes be *converged* on the finger-point $F$, so that Fig. 103 shall represent the actual condition of things. We will observe

FIG. 105. FIG. 106.

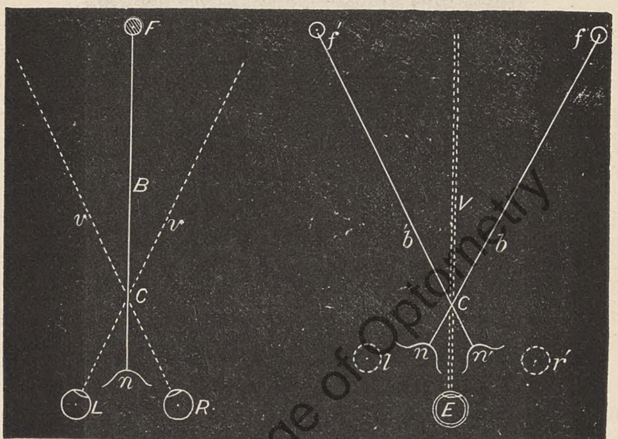



that the double images of the rod represented in the visual result, Fig. 102, approach at their farther end, carrying all objects in the field with them, until they unite at the point of sight $F$, and we have the visual result represented in Fig. 104.

*Experiment 2.*—If by greater convergence we next look at some nearer point $B$ on the rod, as in Fig. 105,

which represents the actual relation of parts, then Fig. 106 represents the visual result. By comparing this with the previous visual results, Figs. 102 and 104, it will be seen that the double images *b b'* approach each other until they unite at the point of sight, and the two images of the rod cross each other at this point, and therefore become again double beyond, but now homonymously. If by still greater convergence we look at a still nearer point *C*, Fig. 107, then the double images of the median rod, Figs 101, 103, 105, will cross at the point of sight *C*, and give the visual result shown in Fig.

FIG. 107. FIG. 108.




108. Finally, if the point of sight by extreme convergence be brought to the root of the nose, then the double images of the nose *n n'*, Figs. 106, 108, will be brought in contact, and the common or binocular field will be obliterated. In all cases it will be observed that the combined eyes look along the combined visual lines through the point of sight, and onward to infinite distance.

It is evident, then, that in optic convergence, as the

two real eyes turn in opposite directions on their optic centers, the two fields of view turn also on the center of the binocular eye in directions opposite to the real eyes, and therefore to each other.

It will be observed that in speaking of visual phenomena I have used much the same language as other writers on this subject, and used also a somewhat similar mode of representation; only I have substituted eyes in the place of the nose, and put noses in the position of the eyes. I have made median lines cross each other at the point of sight, instead of visual lines, and visual lines combine in the middle as a true median visual line. In other words, I have used the true language of binocular vision. I have expressed what we *see*, rather than what we *know*—the language of simple appearance, rather than that mixture of appearance and reality which forms the usual language of writers on this subject.

**Second Law.**—The second law may therefore be stated thus: In turning the eyes together in the same direction, without altering their convergence, *objects* seem *stationary*, and the *visual lines* seem to *move* and sweep over them; but when we turn the eyes in *opposite* directions, as in increasing or decreasing their convergence, then the visual lines seem stationary (i. e., we seem to look in the same direction straight forward), and all objects, or rather their images, seem to move in directions contrary to the actual motion of the eyes. The whole fields of view of both eyes seem to rotate about a middle optic center, in a direction contrary to the motion of the corresponding eyes, and therefore to each other. This is plainly seen by voluntarily and strongly converging the eyes on an imaginary very near point, as for example the root of the nose, and at the same time watching the motion of the images of more

distant objects. The whole field of view of the right eye, carrying all its images with it, seems to rotate to the right, and of the left eye to the left—i. e., homonymously. The images of all objects, as they are swept successively by the two visual lines, are brought from opposite directions to the front and superposed. As we relax the convergence, and the eyes move back to a parallel condition, the two fields with their images are seen to rotate in the other direction—i. e, heteronymously. If we could turn the eyes outward, the two fields and their images would continue to rotate heteronymously. This, which we can not do by voluntary effort of the ocular muscles, may be done by pressing the fingers in the external corners of the two eyes. By pressing in the internal corners, on the contrary, the eyes are made to converge, and homonymous rotation of the fields of view is produced.

Or the law may be more briefly formulated thus: *In convergence and divergence of the eyes, the two fields of view rotate in opposite directions, homonymously in the former case and heteronymously in the latter, about the optic center of the binocular eye* (*œil cyclopienne*), *while the middle or binocular visual line maintains always its position in the median plane.*

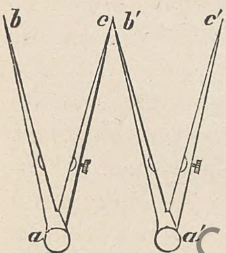
Thus, then, there are two apparent movements of the visual fields accomplished in binocular vision. First, there is a shifting of each field heteronymously a half interocular space. This is involuntary and habitual, and would of itself double all objects heteronymously, separating their images exactly an interocular space. Second, in convergence, there is a rotation of each field about the optic center of the *œil cyclopienne* (or about an axis passing through that center and normal to the visual plane), homonymously. The necessary conse-

quences of these movements are: (*a*) that the images of an object at the point of sight are superposed and the object is seen single, while objects on this side of the point of sight are doubled heteronymously, and those beyond the point of sight homonymously; (*b*) that all objects (different objects) lying in the direction of the two visual lines, whether nearer than or beyond the point of sight, have their images (one of each) brought to the front and superposed; so that the two visual lines are under all circumstances brought together and combined to form a single binocular visual line, passing from the middle binocular eye through the point of sight and onward to infinity.

In all the experiments which follow on this subject it is necessary to get the interocular space with exactness. This may be done very easily in the following manner:

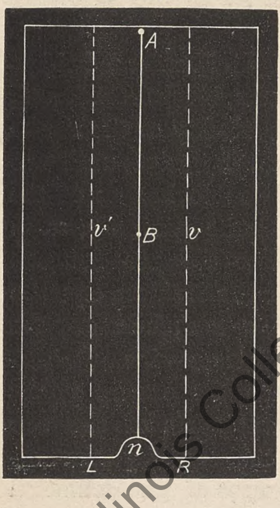
*Experiment.*—Take a pair of dividers and hold it at arm's length against the sky or a bright cloud, and, while gazing steadily at the sky or cloud, separate the points until two of the four double images of the points shall unite perfectly, as in Fig. 109. The distance between the points of the dividers, equal to $a$–$a'$, or $b$–$b'$, or $c$–$c'$, is exactly the interocular distance—i. e., the distance between the central points of the central spots of the two retinæ. The only difficulty in the way of perfect exactness in this experiment is the want of fine definition of the points when the eyes are adjusted for distant vision. This may be obviated by using slightly convex spectacles. The accuracy of the determination may be

FIG. 109.



verified thus: Measure the distance just determined accurately on a card, and pierce the card at the two points with small pin-holes. Now place the card against the forehead and nose, with the holes exactly in front of the two eyes, and gaze through them at a distant horizon or cloud. If the measurement is exact, the two pin-holes will appear as one; their coincidence will be perfect. As thus determined, I find my interocular space exactly 2·44 inches (62 mm.). It will be seen that this method is founded upon the opposite shifting of the two fields of view half an interocular space each, spoken of in the first law. The two pin-holes are seen as one *exactly in the middle*, which is looked through by the *œil cyclopienne;* and this is therefore one of the very best illustrations of such shifting of the two eyes and their visual lines to the middle.

Fig. 110.

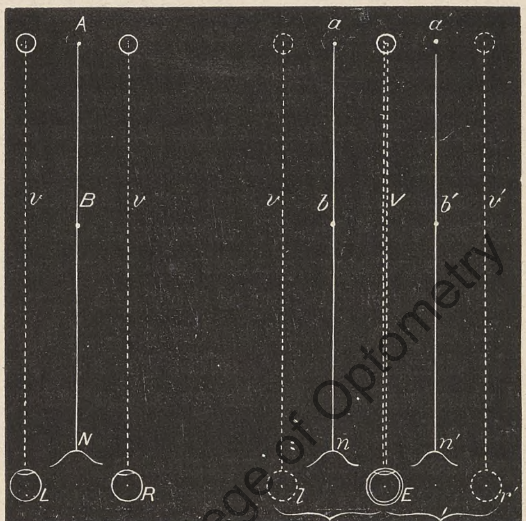



We will now give some additional experiments illustrating and enforcing these two laws, and showing the absolute necessity of using this new mode of diagrammatic representation in all cases in which binocular perspective is involved. For this purpose I find it most convenient to use a small rectangular blackboard about 18 inches long and 10 inches wide, Fig. 110. Mark two points $R$ and $L$ at one end, with a space between exactly equal to the interocular space, and in the middle between these points make a notch $n$ in the edge of

the board to fit over the bridge of the nose. Such a board is admirably fitted for all experiments on binocular perspective.

*Experiment 1.*—Draw a line through the middle of the board from the notch $n$, Fig. 110. This will be the visible representative of the median line; and as the median line is used in all the experiments, this may be made permanent. On this line place two pins at $A$ and $B$. Draw also from the points $L$ and $R$ dotted lines

Fig. 111. Fig. 112.




parallel to the median line and to each other, as the visible representatives of the visual lines when the optic axes are parallel, as when looking at a distant object. Now fit the plane over the bridge of the nose, and place it in a horizontal position a little below the primary plane of vision, say half an inch or an inch, so that the whole surface is distinctly seen, and then look

beyond at a distant object. Leaving out the board in the representations, the actual position of the lines is shown in Fig. 111 and the visual result in Fig. 112. Remembering that in all our figures capitals represent combined or binocular images, simple italics right-eye images, and primed italics left-eye images, it will be seen that the whole board, with all the lines and objects on it and the parts of the face, has been shifted left and right by the two eyes, so that the nose and the median line are seen as two noses and two parallel lines with their pins, separated by a space exactly equal to the interocular space, and the two visual lines are brought together and united in the middle to form a common visual line *V*, as if coming from a single binocular eye *E*. If two small circles be drawn or a pin be set at the end of the dotted visual lines in Fig. 111, these will be united in the result Fig. 112, at the end of the combined visual line *V*. There will also of course be seen to the extreme right and left monocular images of the dotted representatives of the visual lines, and of the circles or pins at their farther end. I have connected by vincula the images of the whole drawing, the primed vinculum being the image of the left eye, the other of the right.

*Experiment 2.*—If we now erase the parallel visual lines *v v* on the board, and draw them convergent on the pin *A*, so that Fig. 113 shall represent the actual condition, and then adjust the board again to the nose and look at the pin *A*, the visual result, or what we shall see, is given in Fig. 114. By comparing this result with the actual condition of things—i. e., by comparing Fig. 114 with Fig. 113—it would seem as if the whole drawing on the board, including the eyes and nose, had been turned about the point of sight *A* by the two eyes in

opposite directions, the right carrying it to the position $l\ A\ E$, the left eye to the position $r'\ A\ E$, shown by

FIG. 113.

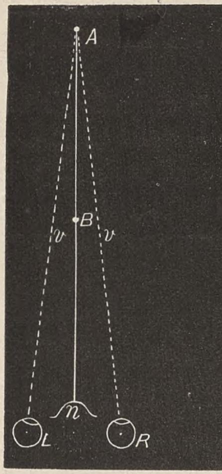
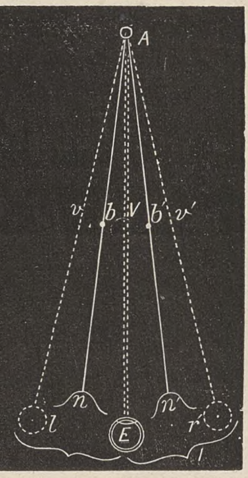
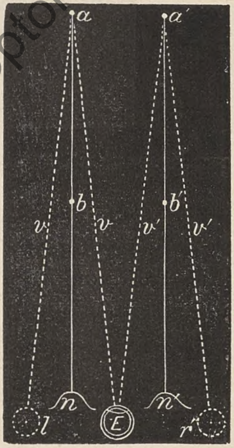



FIG. 114.




the unprimed and the primed vinculum respectively. The *real* nature of the rotation, however, is shown by comparing the appearance of the drawing when the eyes are parallel with its appearance when the eyes are converged on $A$. Fig. 115 represents the visual result when the same drawing is viewed with the eyes parallel. By comparing this figure with the visual result when the eyes converge on $A$ (Fig. 114), it is seen that the two images of the whole drawing rotate on the optic center of the binocular eye $E$, until the pins $a\ a'$ and the visual

FIG. 115.



lines $v\,v'$ of Fig. 115 unite to form the binocular image $A$ and the binocular visual line $V$ of Fig. 114. If the eyes be converged very gradually, the slow approach of the points $a\,a'$, carrying with them the dotted lines $v\,v'$, as if turning on the center of the binocular eye $E$, can be distinctly seen.

*Experiment 3.*—If we again erase the dotted representatives of the visual lines and draw them converging and crossing at the nearer pin $B$, as in Fig. 116, then

FIG. 116. FIG. 117.

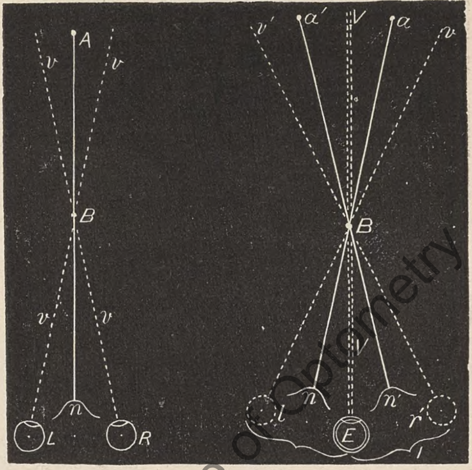



Fig. 117 gives the visual result. It is as if the whole diagram, Fig. 116, had been rotated on the point of sight $B$ in two directions, viz., a right-handed rotation by the right eye and a left-handed rotation by the left eye. But what actually takes place is seen by first gazing at a distant object and comparing the visual result thus obtained, shown in Fig. 118, with that obtained by converging the eyes on $B$, shown in Fig. 117. It is seen that the double images of the whole diagram turn

on the center $E$ until $b$ $b'$, Fig. 118, unite to form $B$, Fig. 117, and $v$ $E$, $v'$ $E$ to form $V$ $E$; and of course the other

Fig. 118.

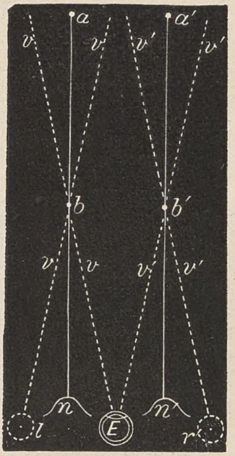
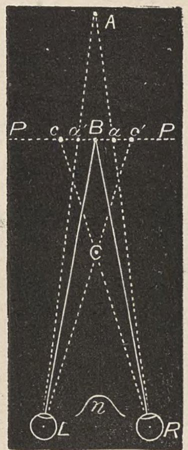



Fig. 119.

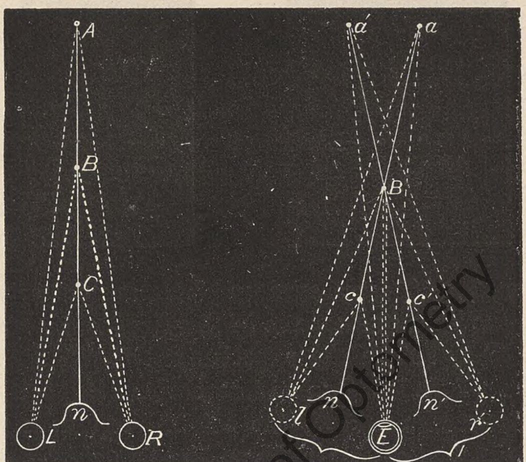



lines, $a$ $a'$, $v$ $v'$, cross over and become homonymous. When the eyes converge as in this last experiment, the points $R$ and $L$ on the experimental board, Fig. 110, must be a little less than an interocular space apart.

Let us now return to the original experiment with three points or objects in the median line given on page 248. We reproduce here the figure (Fig. 119) usually used to illustrate the visual result. We have already shown how impossible it is to represent all the visual results in this way. If we are bent on representing the parallactic position of the double images, then we must refer them all to the same plane, as in Fig. 119; but this is false. If, on the other hand, we try to place them at the distances at which we actually see them, observing the law of direction, then the double images unite, which is also false.

*Experiment 4.*—Now try the same experiment by the use of the board, and the true mode of representation becomes manifest. On the median line, Fig. 120, place three pins, and draw dotted lines to each of them from the position of the eyes, which shall be the visible representatives of either visual lines or ray-lines. As in the experiment the eyes will look at *B*, let the dotted lines to *B* be stronger to represent visual lines;

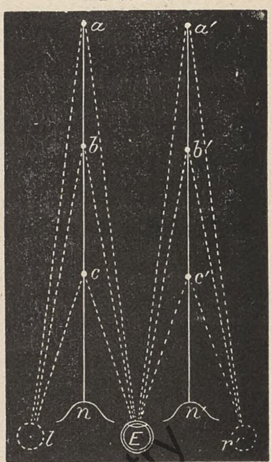
FIG. 120. FIG. 121.




then the others will represent only ray-lines. Now when this diagram is observed with the point of sight at *B*, Fig. 120, then the *visual result*—i. e., what we actually see on the board—will be Fig. 121. It is seen that the whole diagram Fig. 120 is rotated in opposite directions about the point of sight *B* to make the result, Fig. 121. But the real nature of the rotation is shown by comparing the result with the eyes parallel, Fig. 122, with the result with the eyes converged on *B*, Fig. 121.

With the eyes parallel, the whole diagram is simply doubled heteronymously by each eye shifting it half an interocular space in opposite directions. Now converging the eyes slowly, the two images of Fig. 120 shown in Fig. 122 are seen to rotate on $E$ until the points $b$ $b'$ and the dotted lines $b$ $E$, $b'$ $E$ unite to form $B$ $E$, Fig. 121. In doing so, $c$ $c'$ have approached, but not united; they are therefore still heteronymous, while $a$ $a'$ have met and passed each other, and become homonymously double.

Fig. 122.

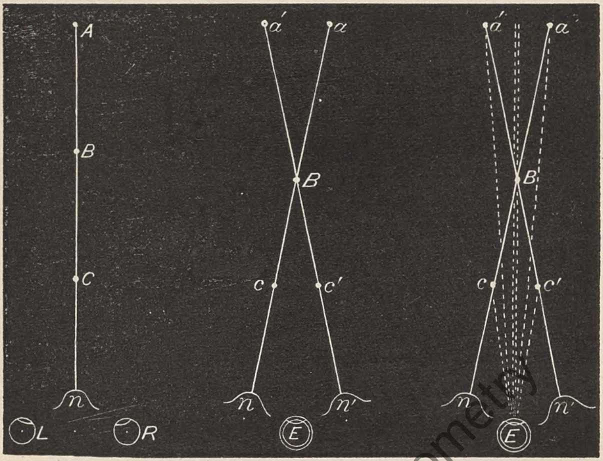



Therefore Fig. 121 truly represents all the visual facts. It gives both the parallactic position of the points in relation to the observer, their relative position in regard to each other, and their relative distance. Or, if we leave out in the original diagram, as complicating the figure, all except the necessary median line and pins, as in Fig. 123, then the visual result is given in Fig. 124. Or, adding in the visual result only the visual line and the most necessary ray-lines, viz., those going to the binocular eye, we have Fig. 125. This last figure we shall hereafter use to represent the phenomena of binocular perspective.

**Application to Stereoscopic Phenomena.**—We wish now to apply this new method of representation to the phenomena of the stereoscope. We reproduce here as Fig. 126 the diagram used on page 150. It is seen that while the different distances, $A$ and $B$, at which the

foreground and background are seen, are truly represented, no attempt is made to represent the double images of the foreground when the background is regarded, or *vice versa.* It is impossible by this usual method to represent these double images without refer-

Fig. 123. Fig. 124. Fig. 125.

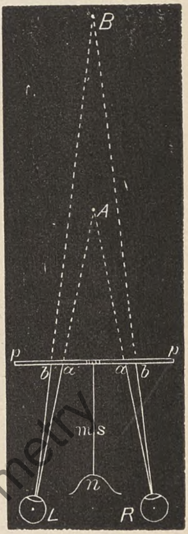



ring them to the same plane; but this would of course destroy the perspective, which it is the very object of the diagram to illustrate. The new method, on the contrary, represents the true distance of the point of sight, and the true positions and distances of the double images, and therefore the true binocular perspective. In other words, it represents truly all the binocular visual phenomena. It will be best to preface this explanation by an additional experiment.

*Experiment.*—If a rectangular card, like an ordinary stereoscopic card, or a letter envelope, be held before the face at any convenient distance while the eyes gaze on vacancy, i. e., with the optic axes parallel, the two

images of the card will be seen to slide over each other heteronymously, each a distance equal to a half interocular space, and therefore relatively to each other exactly an interocular space. If the card be longer than an interocular space, there will be a part where the two images will overlap.

Fig. 126.

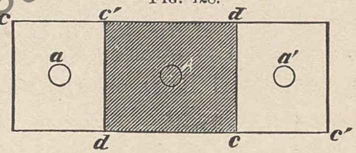



This is represented in the accompanying diagrams, of which Fig. 127 represents the card when looked at, and Fig. 128 the visual result when the eyes are parallel. In this visual result *c c* is the right-eye image of the card, *c′ c′* the left-eye image, and *d d* the binocular overlapping. This overlapped part will be opaque, because nothing can be seen behind it by either eye. But right and left of this are two transparent spaces. That on the left belongs to the image of the right eye, but not to that of the left, and therefore the left eye sees objects beyond it. That on the right belongs to the left eye, but the right eye sees objects beyond it.

If two circles, *a a*, be drawn on the card, Fig. 127, an interocular space apart, they will unite into a binocular circle *A* in the center of the opaque part, Fig. 128, while two monocular circles *a a′* will occupy the transparent borders.

Fig. 127.


Fig. 128.



By the law of alternation spoken of on page 108, sometimes the right eye will prevail, the right-hand transparent border will disappear, and the whole right-eye image *c c* will appear opaque. Then the left eye prevails, and the left-hand border will disappear, and the whole left-eye image *c′ c′* will appear opaque. Sometimes both borders disappear, and only the binocular overlapping is seen. Sometimes the whole double image, including both borders, becomes opaque. But the true normal binocular appearance or visual result is given in Fig. 128—i. e., opaque center and transparent borders, these borders being exactly equal to the interocular space.

We are now prepared to show how stereoscopic phenomena may be represented by our new method. In Fig. 129, *c c* represents a stereoscopic card in position; *m s*, the median screen, which cuts off the supernumerary monocular images; *a a*, identical points in the foreground of the pictures, and *b b*, in the background. The two eyes and the nose are represented as before by *R*, *L*, and *n;* and *a R*, *a L*, *b R*, *b L* are ray-lines. Leaving out the dotted lines beyond the card, this diagram represents the actual condition of things. The dotted lines beyond the picture show the mode of representation usually adopted. When the eyes are directed to *a a*, then *a R*, *a L* become visual lines, and *a a* are united and seen at the point of sight *A*. When the eyes are directed to *b b*, then *b R*, *b L* become visual lines, and *b* and *b* are united and seen single at the point of sight B.

The defect of this mode of representation is, that it takes no cognizance of the double images of *b b* when *A* is regarded, or of *a a* when *B* is regarded. The attempt to represent these would destroy the perspective.

By our new method, on the contrary, all the phenomena are represented. In Fig. 130 is shown the visual result when the eyes are fixed on the background; in Fig. 131, the visual result when the eyes are fixed

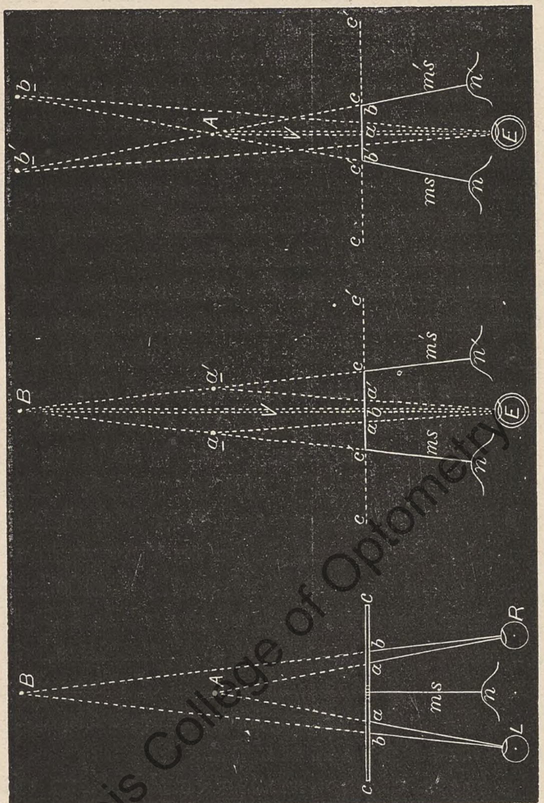


Fig. 129. Fig. 130. Fig. 131.

on the foreground. In Fig. 130 we see that the nose $n$ $n'$ and the median screen *ms m′s* are doubled heteronymously, and the space between the two is the common and only field of view (for the monocular fields

are cut off by the screen). In the middle between these is the binocular eye *E*, looking straight forward. This is manifestly exactly what we see in the stereoscope. Again, we see that the two images of the card have slidden over each other, in such wise that *b b*, Fig. 129, are brought together in the middle, united, and seen single in Fig. 130. But where? at what distance? Evidently this can only be at the point of sight, which, as I have already explained, is, in diagrammatic representations of visual phenomena, where the common visual line and the two median lines meet one another at the point *B*, Fig. 130. Meanwhile *a a*, Fig. 129, will have crossed over and become heteronymous, and their double images *a a′*, Fig. 130, will be seen just where their ray-lines *E a* and *E a′* cut the median planes, viz., at *a a′*. In Fig. 131, which is the visual result when the eyes are fixed on the foreground, the shifting or sliding of the two images of the card is not quite so great as before. It is only enough to bring together the nearer points *a a*, Fig. 129, but not *b b*. These latter, therefore, are homonymously double. The united images of *a a* are seen single on the common visual line, and at the distance *A* where the double images of the median line cross each other; while *b b* are seen homonymously double, and at *b b′*, the intersection of their ray-lines with the continuation of the median lines after crossing; for homonymous images are always referred *beyond* the point of sight.

The mode of representing combinations with the naked eyes by squinting is similar. Of course the place of the combined picture will in this case be between the eyes and the card. I reproduce (Fig. 132), for the sake of comparison, the usual mode of representation from page 153. In order to make the perspective nat-

only does the diagram give truly the place and distance of the combined image, but also of the double images by means of which perspective is perceived.

It will be remembered that double images may be nearer or farther off than the point of sight, but that in the former case they are heteronymous, in the latter homonymous. In this way we at once perceive their distance in relation to point of sight. Now, in the new mode of representation, this fact is also indicated. In both of the figures 133 and 134 there are two places where the ray-lines cut the median lines, and therefore where double images may be formed; but in the one case the images are heteronymous, and therefore we refer them to the nearer points $\underline{a}$ $\underline{a}'$; in the other case they are homonymous, and therefore we refer them to the farther points $\underline{b}$ $\underline{b}'$.

If stereoscopic pictures mounted in the usual way be combined with the naked eyes by squinting, or pictures with reverse mounting be combined in the stereoscope, the perspective will be inverted. In this case the diagrammatic representation is exactly the same, except that the double images of points in the foreground *a a'* will now be homonymous, and therefore referred to the other possible point of reference, viz., beyond the point of sight; and double images of points in the background *b b'* will become heteronymous, and therefore referred to the nearer point.

*Some curious Phenomena illustrating the heteronymous Shifting of the two Fields of View.*

*Experiment 1.—To trace a picture where it is not.* Take a postage stamp, or a piece of coin, or a medallion, or a small object or picture of any kind; place it on a sheet of white paper. Take then a thin opaque screen,

like a pamphlet, or thin book, or piece of cardboard, and set it upright on the *right side* of the object or picture, and bring down the face upon the top edge of the screen, in such wise that the latter shall occupy the median plane. If we now gaze with the eyes parallel —i. e., on vacancy—the median card will double and become two parallel cards, and in the middle between them will be seen the object or picture. With a pencil in the right hand we may now trace the outline of the object or picture, by means of its image, on the right side of the screen, although the actual object or picture is on the left side of the same.

The accompanying diagrams illustrate and explain the phenomena. In Fig. 135, *R* and *L* are the two

FIG. 135.

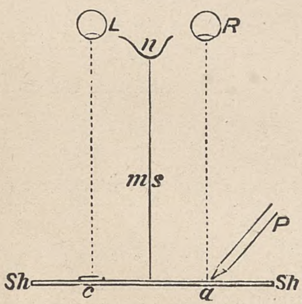
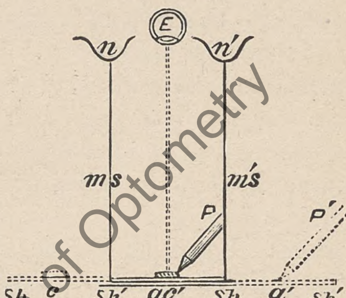



FIG. 136.



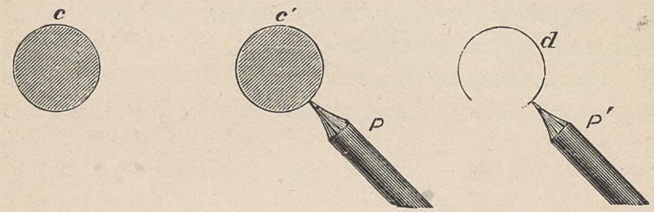

eyes looking *down* on the paper sheet *sh; ms* is the median screen, and *c* the coin on its *left side; a*, the spot where the outline is traced with the pencil *P*. This figure therefore gives the actual condition of things. The visual result, and therefore the explanation, is given in Fig. 136. By careful inspection it is seen that the screen is doubled heteronymously, and becomes two parallel screens *ms*, *m's;* that the two images of the

paper sheet are slidden over each other, so that the left eye, its visual line, and its image of the coin *c* are all brought to the middle, while the right eye, its visual line, and its image of the pencil and of the point *a* are also brought to the middle from the other side, and superposed. We therefore see the image of the coin and trace its outline exactly an interocular space distant from its real position. If it were not for the screen, there would be another (right-eye) image of the coin and another (left-eye) image of the pencil and of the point *a*. These I have indicated in dotted outline.

*Experiment 2.*—If we make the experiment without the use of the median screen, then the cause of the phenomenon becomes obvious. If we lay a piece of money on a sheet of paper, and then gaze in the direction of the coin, but with the eyes parallel—i. e., on vacancy—the money of course separates into two images an interocular space apart. If we approach this with a pencil for the purpose of tracing the outline, we will see the pencil also doubled. If we now bring corresponding images in contact—i. e., right-eye image (left in position) of the pencil with the right-eye image (left in position) of the coin—we touch the coin with the pencil. But if, on the contrary, we bring the right-eye image (left in position) of the pencil to the left-eye image (right in position) of the coin, we may trace the outlines of the piece an interocular space distant from its true position. This is shown in Fig. 137, which gives the visual result of such an experiment—*c* and *c′* being the right- and left-eye images of the coin, and *P* and *P′* of the pencil. If, while the operation is going on, we observe carefully, we will see to the right the left-eye image of the pencil, *P′*, engaged in making a tracing. But there is no tracing in this place; it is

only the left-eye image of the real tracing being made by the other pencil $P$. In the previous experiment the screen cuts off all the images except the right-eye image

FIG. 137.




of the pencil and the left-eye image of the coin, which are brought together in the middle.

Tolerably good tracings of a picture may be made in this way. The only difficulty in making them really accurate is the unsteadiness of the optic axes, and therefore of the place of the image. I have, however, used this method in making outline tracings of microscopic objects, which may be filled out afterward. For this purpose a card is placed on the right side of the microscope, and the microscopic object is viewed with the left eye, while the right eye is used for guiding the pencil. Precisely as in the experiment with the coin (Fig. 137), the left-eye image of the object and the right-eye image of the pencil and of a certain spot on the card are brought together in the middle.

*Experiment 3.—To trace the outlines of a light on an opaque screen.*—The same experiment may be modified in an interesting way thus: Set a light in front of you on a table. Place a median screen of cardboard or of tin between the eyes, so that the light can be seen with both eyes. Now bend the screen to the right so as to make a right angle at the distance of 6 or 8 inches from the eyes. This part will cut off the view of the

candle-flame from the right eye. Nevertheless, while gazing steadily at the flame, a really correct outline of it may be drawn on the opaque transverse screen, precisely as if it were transparent. This is illustrated and explained by the accompanying diagrams. Fig. 138 is the actual condition of things. *F* is the flame; *ms*, the median screen, resting on the nose *n*; *ts*, the transverse portion of the screen. Now, just where the

Fig. 138.

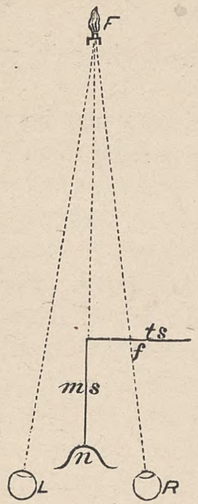
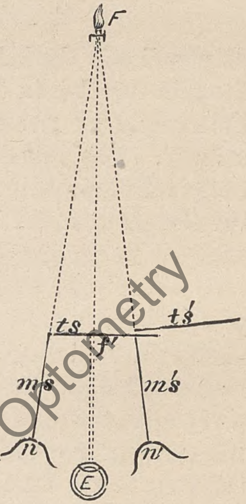



Fig. 139.

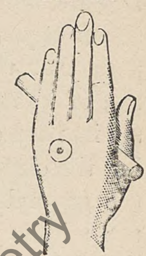



visual line of the right eye pierces the transverse screen, viz., at *f*, we may draw the picture of the flame *F*, precisely as if it were transparent. The explanation is found by examining the visual result, Fig. 139. By the heteronymous doubling of the median and transverse screens, the left-eye image of the flame and the right-eye image of the transverse screen *ts* are brought together, and the flame may be seen as it were through

the opaque screen as a transparency, and drawn at $f'$. In order to show that the flame is seen only by one eye, I have stopped one of the combined visual lines at the screen. The apparent transparency of an opaque screen in this case is precisely the same as the transparent borders of an opaque screen mentioned and explained on page 275.

*Experiment 4.—To see through a book, a deal board, or the back of the hand, or even if necessary through a millstone.* Roll up a thin pamphlet into a hard tube a half or three quarters of an inch in diameter, and hold it with the left hand between the thumb and hand, as shown in Fig. 140. Place the right eye to the end of the tube and look through the tube at the opposite wall, or still better at a map or picture hanging on the wall, while the back of the hand conceals the map or picture from the left eye. A circular spot on the wall or map will be seen through the center of the hand (Fig. 140), precisely as if there were a circular hole in the hand. Of course a book or an opaque plate of any kind may be substituted for the hand in this experiment.

FIG. 140.



The explanation is as follows: The visual line of the right eye passes through the axis of the tube and pierces the center of the circular visible area of the object regarded, while the visual line of the left eye pierces the back of the hand or the book at a point distant from the axis of the tube just an interocular space, or about $2\frac{1}{2}$ inches. By the right and left shifting of the fields of view already explained, the two visual lines are brought together in the middle; and therefore the center of the area regarded by the right eye and the

spot on the hand or book pierced by the left visual line are also brought together and superposed.

One thing more to complete the explanation: The impression on the right eye prevails over that on the left — the impression of the circular area obliterates that of the corresponding area on the hand or book for two reasons: first, because the circular area is strongly differentiated from the rest of the right-eye field of view (i. e., the dark interior of the tube), while the corresponding or coincident area of the left-eye field (the hand or book) is not thus differentiated; and second, because both eyes are focally adjusted for the distance of the object seen by the right eye only. Thus it happens that the right eye sees only the circular area, the rest of its field being very dark; while the left eye sees all its field except the spot corresponding to and covering the circular area. Thus the binocular observer sees the general field of the left eye (the hand or book), in the middle of which he also sees the circular area of the right-eye field. But if an ink-spot be made on the back of the hand or book just where the left visual line pierces it, the impression of this will be strong enough to resist obliteration; the strongly differentiated ink-spot will be seen in the center of the circular area, as shown in Fig. 140.

## CHAPTER V.

### *VISUAL PHENOMENA IN OCULAR DIVERGENCE.*

The only normal condition of the optic axes is either parallelism or convergence. We can not voluntarily make the optic axes divergent, because there is no useful purpose subserved by such a position; there would be no meeting of the optic axes, and therefore no point of sight. All the advantages of binocular vision are conditioned on convergence only. Divergence would only confuse by giving false information. But, although the power of divergence could be of no use and has therefore never been acquired, yet under certain circumstances divergence does occur, and the curious phenomena which then follow are an admirable illustration of the principles of binocular vision already set forth. We will give a few of these phenomena.

1. **In Drowsiness.**—It is well known that in extreme drowsiness, when we lose control over the ocular muscles, we see double images. It is usually believed and taught by physiologists that this is the result of *convergence* of the optic axes in sleep. I know of no observations purporting to prove this. It is probably an inference from the contracted state of the pupils in sleep, and the fact that contraction of the pupils is

usually consensual with optic convergence.* This view is certainly false. Double images in sleepiness are certainly due to *divergence*, not convergence, of the optic axes.

In extreme drowsiness I have often observed the object which I was regarding (it might be the head of a dull speaker) divide into two images, which then separated more and more, until at a distance of 30 feet they were 10 to 15 feet apart. Even under these conditions I have found it possible to make a scientific experiment. Often, control over the ocular muscles is lost even while consciousness and control over mental acts is still perfect. Often, although by effort I could retain control over the eyes, I have chosen to abandon it in order to make the following experiments.

*Experiment 1.*—As soon as the images are well separated, I wink the *right* eye: immediately the *left* image disappears. The images are therefore *heteronymous*. But convergence produces homonymous images, while parallelism and, *a fortiori*, divergence produce heteronymous images. In this case the heteronymous images can not be produced by mere parallelism, because this state separates the images only an interocular space, or about 2½ inches, whereas the images may be separated many feet: therefore they are produced by *divergence*. The amount of divergence is easily calculated. At a distance of 30 feet a separation of the double images of 10 feet would require an angular divergence of the optic axes of nearly 19°; a separation of 15 feet would indicate an angular divergence of 28°.

* "In sleep and in sleepiness both eyes are turned *inward* and upward." "The contracted state of the irides in sleep is a consensual motion dependent on the position of the eyes, which are turned inward and upward."—Müller, "Physiology," Am. ed., pp. 810 and 535.

In every such experiment the consciousness is quickly and completely aroused, and the double images are speedily reunited, though not so speedily but that the result is unmistakable. But, lest some may regard the speedy union of the images as an objection to this experiment, we will take another.

*Experiment 2.*—While lying abed in the morning, if one gazes on vacancy, objects near at hand (say the bedpost) are doubled heteronymously, the images being $2\frac{1}{2}$ inches apart. If, while thus gazing and observing the heteronymous images, one should be overtaken by drowsiness and consequent loss of control over the ocular muscles, he will see that the already heteronymous images separate more and more. Now, if this were due to convergence, the heteronymous images would approach, unite, cross over, and become homonymous.

It is certain, then, that in myself, in extreme drowsiness, when control over the ocular muscles is lost, and therefore presumably in sleep, the eyes *diverge*. I have also satisfied myself that my case is not exceptional in this respect, for my results have been verified by several other persons. I think, therefore, I may assume it as a general law.

Double vision is also a well-known phenomenon of extreme intoxication. The unnatural appearance of the eyes in such cases is due to want of parallelism of the optic axes. I have on several occasions examined the eyes of those in this sad condition, and have always found the axes divergent. This seems to arise from partial paralysis of the ocular muscles.

If we examine the eye-sockets of a human skull, we find that their axes diverge about 25°–30°. This is about the extreme divergence of the optic axes in

drowsiness. It is probable, therefore, that in a state of perfect relaxation or paralysis of the ocular muscles the optic axes coincide with the axes of the conical eye-sockets, and that it requires some degree of muscular contraction to bring the optic axes to a state of parallelism, and still more to one of convergence, as in every voluntary act of sight. In the human eye, therefore, and also in that of the highest animals, there are three conditions of the optic axes: first, convergence, as when we look at a near object; second, parallelism, as when we look at a distant object or gaze on vacancy; third, *divergence*, when we lose control over the ocular muscles, as in drowsiness, in drunkenness, in sleep, and in death. The first requires a distinct voluntary contraction of the ocular muscles; in the second there is no voluntary action, but only that involuntary tonic contraction characteristic of the healthy waking state; in the third the relaxation is complete. The first is the *active* state of the eye, the second the *waking* passive state, the third the absolutely passive state.

**2. Other Modes of producing Divergence.**—But the divergence of the optic axes may be effected in other ways. In most normal eyes the passive state is one of parallelism. It is easy therefore to double homonymously the images of an object at any distance by convergence, but most persons would find it impossible voluntarily to double the images of a very distant object, as for example a star, heteronymously—i. e., by divergence. Yet under certain conditions a slight divergence is possible. For example, I find I can (and I believe most persons can) combine with the naked eyes and with natural perspective (i. e., beyond the plane of the card) stereoscopic pictures in which identical points are farther apart than the interocular distance. I can

not always succeed, being able to do so only when my mind is in an exceptionally passive state.

*Experiment 3.*—I take now a skeleton stereoscopic diagram, identical points in the background of which are separated by a space greater by an eighth of an inch than my interocular space. By holding it at arm's length so as to make the divergence as small as possible, I succeed in combining. After the combination is stable, I can bring the card nearer and nearer until it is within 5 inches of my eyes, and yet the combination is retained. But this corresponds to a divergence of only $1\frac{1}{2}°$.

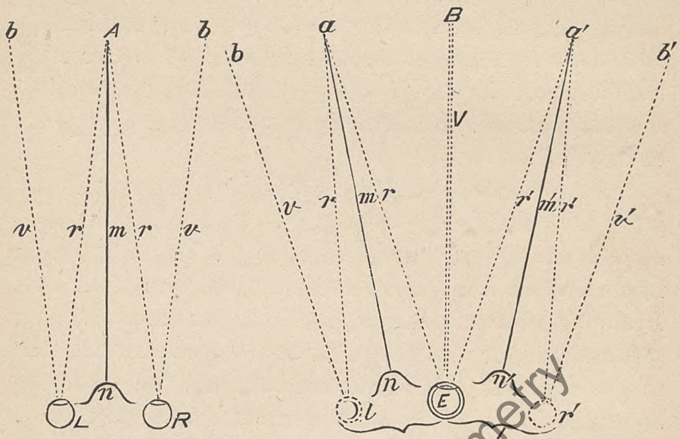
*Experiment 4.*—But by mechanical force we may make the eyes diverge 40° or 50°. This is done by pressure in the external corner of the eye. By thrusting a finger of each hand into the external corners of the eyes I can make the two images of an object directly in front separate 50°, or the images of two objects situated 25° to the right and left of the median line, and therefore 50° apart from each other, come to the front and unite.

The following diagrams represent and explain the visual phenomena in divergence of the optic axes.

In Fig. 141, which represents the actual relation of parts, *m* is the median line; *v v*, the visual lines or optic axes produced; *A*, an object on the median line; *b b*, two similar objects in the direction of the diverging visual lines; and *r r*, ray-lines from the object *A*. Fig. 142 shows the visual result if the lines in Fig. 141 were visible lines drawn on the plane described on page 266. It will be seen that by heteronymous shifting and then heteronymous rotation the whole diagram represented by Fig. 141 has been carried and rotated by the right eye to the position of the lines connected by the unprimed vinculum, and by the left eye to the position

of the lines connected by the primed vinculum. By this means the two visual lines *v v* are brought together and combined as the common visual line *V*, and two of the images of the objects *b b* are brought together and superposed at *B*; the median line is doubled and ro-

FIG. 141. FIG. 142.



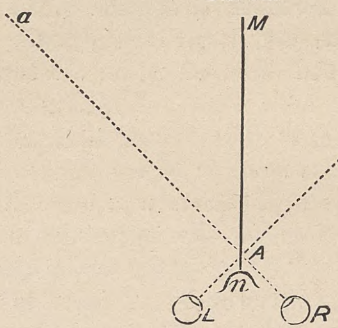

tated heteronymously to the positions *m m′*, carrying with them the double images of the median object *A* as *a a′*. The above diagram correctly represents the position and the distance of the double images *a a′*, and the *position* of the combined image *B*, but can not represent the *distance* of the combined image, *because there is no point of sight.* For the point of sight is *really* the point of optic convergence or *meeting of visual lines*; in *diagrams* representing visual results, it is the point *of crossing of the doubled median lines*; but this point, by both definitions, would be in this case behind the head. The diagram therefore correctly represents *all* the visual facts; for, there being in divergence

no point of sight, the distance of objects in the visual line is indeterminate as represented. It is impossible by the usual method to correctly represent *any* of the visual facts.

**3. If the Law of Direction be opposed to the Law of Corresponding Points, the Latter will prevail.**—These two most fundamental laws of vision are sometimes in discordance with each other. The reason of this may be thus explained: The law of direction is the fundamental law of monocular vision, as the law of corresponding points is of binocular vision. Now, for each eye, and therefore for the monocular observer, direction is determined by reference to the *optic axis*, but for the binocular observer by reference to the *median line*. On account of this difference of line of reference, while objects seen single are seen in their true positions, double images are always seen in positions different, and in some cases widely different, from the object which they represent. The difference may even amount to 45°. For example: The binocular field of view in my own case is 100° in a horizontal direction. By strong convergence I can nearly bring the double images of the root of my nose together, and thus obliterate the common field. I am sure therefore that I can make the optic axes of my two eyes cross each other at right angles. In such a case, of course, objects directly in front are doubled and their images separated 90° from each other, while objects lying to the right and left 90° from each other are brought to the front and their images superposed. Here the images are 45° from the true position of the objects which they represent. Thus Fig. 143 represents the actual relation of things in this case, and Fig. 144 the visual result, showing that the positions of the objects $M$ and $a\ a$ are com-

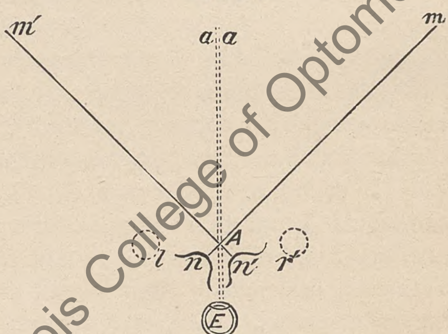
pletely reversed. It may indeed be said that the case of *a a* seen in front may be reconciled with the law of direction. For, if the combined images be referred to

Fig. 143.




the point of optic convergence *A*, as in the usual mode of representation, then each eye sees its own object in its true direction, but only mistakes its distance. To

Fig. 144.




this I would answer that *each eye* does indeed give the true direction, as is quickly shown by shutting one of them, but the *two eyes* together do not. Each sees its

own object in the true direction, but the *binocular observer* sees their combination in a wrong direction. In the case of the double images $m$ and $m'$ (Fig. 144) of the object $M$ (Fig. 143), it is still more difficult to explain their apparent position by the law of direction.

**A curious Corollary.**—It is seen that, under all circumstances, if the median visual plane coincides with the median plane of the head, whatever be the position of the optic axes, objects in the visual lines are moved to the front and seen there. Now the same would be true if our eyes were turned directly outward right and

FIG. 145.

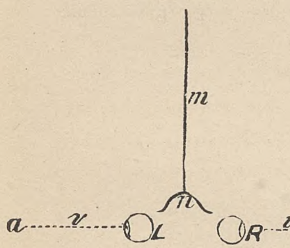
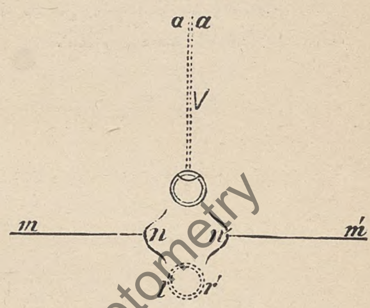



FIG. 146.




left. There can be no doubt that if we could turn our eyes directly outward, or if our eyes, retaining their present organization and properties in regard to corresponding points, were transferred to the sides of the head with their axes straight right and left—i. e., making an angle of 180° with each other—*images of objects in the direction of these axes*, and therefore directly right and left, would be moved round 90° each, and combined and seen directly in front. This seems an extraordinary result, but it is a necessary consequence of the law of corresponding points. The retinal images of the two objects are on corresponding

points, viz., on the central spots; therefore, by the law of corresponding points, they must be seen as *one*. But where else can this take place but in front? The accompanying figures are a diagrammatic representation of these facts, Fig. 145 being the supposed condition of things, and Fig. 146 the visual result. After the frequent explanations of similar figures, a bare inspection will be sufficient.

It is needless to say that this is a purely hypothetical case. If any animals have their eyes so placed —i. e., on the sides of the head, and therefore optic axes like Fig. 145—they can not have corresponding points nor binocular vision. But of this we will speak further in the next chapter.

# CHAPTER VI.

## *COMPARATIVE PHYSIOLOGY OF BINOCULAR VISION.*

As we can not enter into the consciousness of animals, nor communicate intelligibly with them in regard to their visual experiences, we can only judge of these by the structure of their eyes. Three points of structure are important in this regard, viz., the *optic chiasm*, the *position* of the *optic axes*, and the presence or absence of a *fovea*.

*Optic Chiasm.*—It will be remembered that in man, and also probably in most vertebrates, the optic roots, after leaving the brain, converge and unite to form the chiasm, and then again diverge as the optic nerves enter the eye sockets, pierce the eye, and spread out to form the retinæ. Furthermore, that in the chiasm the fibers of the roots partly *cross over* to form the fibers of the optic nerve on the *other side*, and partly do not cross over, but go to form the fibers of the optic nerve on the *same* side. This is shown diagrammatically in Fig. 41, page 119. Therefore each root supplies both optic nerves, and therefore both eyes, and conversely each eye is supplied by both roots and both sides of the brain. Still further, it is probable that the fibers of each root supply *corresponding halves* of the two eyes. There seems to be no doubt, therefore, that the optic chiasm, and especially this peculiar partial crossing of

the fibers, is in some way—imperfectly understood—intimately connected with the use of the two eyes as one instrument—i. e., with binocular vision. I said especially the peculiar *partial* crossing, because by this arrangement each side of the brain controls both eyes. The bodily crossing over of fibers would not have this effect, for then each side of the brain would supply the opposite eye.

Now the optic chiasm, with its peculiar partial crossing of fibers, is probably present in all mammals and birds, and possibly in reptiles and amphibians. These, therefore, probably have, in a greater or less degree, perhaps imperfectly, the phenomena of binocular vision. But in fishes the fibers of the optic roots seem to cross bodily over to form the optic nerve on the other side. There is therefore in them no *true* chiasm, and therefore no true consensual movement of the two eyes and no binocular vision. We shall find other reasons for coming to this conclusion presently.

Nothing at all resembling an optic chiasm is found in any invertebrate. It is characteristic of vertebrates. *No invertebrate enjoys the phenomena of binocular vision.*

*Position of the Optic Axes.*—In man the axes of the eye-sockets diverge about 25° from one another, or about 12° each from the median plane of the head. In these slightly divergent sockets the eyeballs are so placed that their optic axes are *parallel* in a natural or *passive state.* This is evidently the most favorable position for easy convergence of the axes on an object at any distance, and therefore for binocular vision. A less divergence of the sockets, though still more favorable for convergence on a very near object, would produce too small an interocular base for accurate binocu-

lar judgment of distance; a greater divergence would destroy parallelism of the optic axes in a *passive* state —i. e., would require voluntary effort to produce and maintain parallelism.

The apes are exactly like man in this regard. In them, too, the eyes are naturally parallel in a passive state, and are therefore perfectly adapted for binocular vision. But as soon as we go lower down the vertebrate scale the eyes are placed wider and wider apart, the axes of the eye-sockets become more and more divergent, and with them the normal passive position of the *optic axes* become also more and more divergent, until finally in fishes the eyes are placed on the sides of the head with their optic axes divergent nearly or quite 180°. It is evident that eyes so placed can have no common field of view, no common point of convergence, no point of sight, and no binocular vision. Each eye moves and sees independently of the other. This may be seen by watching fishes in an aquarium.

In all mammals, however, except perhaps the whales, the divergence of the eye-sockets is not so extreme but that by voluntary effort they may be made to converge with their optic axes on an object. They therefore have binocular vision in various degrees of perfection—more perfect in carnivores, less perfect in herbivores, but in all less perfect because less important than in man. For them wideness of view is more important than attentive examination and accurate binocular judgment of distance. For example, in ruminants the eyes are placed on the extreme margins of a broad front, perhaps six inches apart, and are very protuberant. This together with the horizontal elongation of their pupils gives them a very wide field of view. There is no doubt that the view of a grazing ruminant sweeps the

whole horizon without moving the eyes or turning the head. The advantages of easy convergence are sacrificed to the greater advantages of a wide view.

*Birds* usually have their eye-sockets widely divergent, often 90° to 100° (Fig. 147). Their optic axes also seem nearly or quite coincident with the socket axes. This divergence is far too great to admit of easy convergence of the optic axes on an object, especially a near object. Yet most birds certainly have binocular vision. To make this possible, however, there is a peculiar and unique retinal structure, of which we shall speak under the next head.

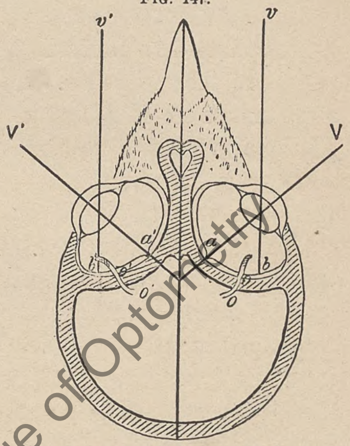
*Fovea.*—It will be remembered that in man this most highly organized spot is situated at the point where the optic axis pierces the retina. It is in the very center of the retinal concave, and about it the corresponding points of the two retinæ are symmetrically arranged. In every act of looking, the images of the object looked at are made to fall on these spots. This is the necessary condition of accurate vision. We have usually called it the *central spot* because of its central position. In speaking of the human eye this is well, but in comparative anatomy it is better to call it the *fovea*, because it *is not always central.*

Now in mammals—although there is usually a more highly organized central *area*—a true *fovea is wanting*, except in the *anthropoid apes.* In these latter the retinal structure is precisely like man's in this regard. In mammals, however, except in apes, extremely accurate vision of single objects is largely sacrificed to the greater advantages of a tolerably clear vision over a very wide field. Their safety depends on this latter. It will be remembered (page 79) that in man the parts of the retina at a little distance from the fovea are more

sensitive to light than the fovea itself, though accurate observation of outline and details of surface are seen only by the fovea. Mammals' eyes are as sharp as, perhaps sharper than, ours, to *detect the presence* but not to *discern the nature* of objects. This is probably the reason that they are so easily startled by unaccustomed objects.

The case of birds is peculiar. The wide divergence of their optic axes (Fig. 147) would make binocular vision impossible for them *if their corresponding points were arranged like ours*—i. e., symmetrically about a *central* fovea. But, strange to say, some birds—perhaps most—*have two foveæ* in each eye, one *central*—i. e., in the optic axes (Fig. 147 *a*)—the other in the temporal half of the retina and excentral by about 60° (Fig. 147 *b*). These latter are so placed that lines drawn through them and through the center of the pupils are parallel each to the median plane of the head and therefore to one another. Evidently these temporal foveæ are suitably placed for convergence on a common point of sight, and therefore for binocular vision. Evidently also corresponding points must be arranged about these as with us about the central foveæ. Evidently their central foveæ can be used only for *monocular* not

Fig. 147.




SECTION OF BIRD'S HEAD. (After Slonaker) *V V'*, monocular visual lines; *v v'*, binocular visual lines; *a a'*, *b b'*, central and temporal foveæ respectively.

for binocular vision. But it is this central fovea which is the *most distinct* and therefore most highly organized. Therefore their binocular vision is *less perfect* than ours, or even *than their monocular* vision. Hence it is that a bird when it wishes to look attentively turns the head and looks with one eye so as to bring the image on the *central* fovea. So far as the central fovea is concerned they use their eyes independently of one another—each eye looks for itself.

Neither of these two foveæ of birds can be regarded as homologous with that of man. Taking the entrance of the optic nerve—or the blind spot *o* as the term of comparison—our fovea is *temporal*, but it is *central* in regard to the optic axis. In birds the entrance of the optic nerve or blind spots is between the two foveæ. The one is central to the optic axis but nasal to the blind spot, the other is, like ours, temporal to the blind spot but excentral to the optic axis.

Foveæ and corresponding points are probably developed together, and both their existence and their place is determined by the position of the eyes and the habits of the animal, especially in looking attentively.

Thus then, judging alike from the chiasm, the position of the eyes, or by the existence and position of the fovea, we conclude that binocular vision becomes less and less perfect as we descend the scale and finally disappears in the lowest vertebrates. In invertebrates we find nothing at all like a chiasm nor a fovea. In many of them the eyes are also immovably fixed. We are justified in thinking that the phenomena of binocular vision do not exist in them.

# CHAPTER VII.

## *THE EVOLUTION OF THE EYE.*

The history of the origin and gradual evolution of this most refined instrument has always been regarded as among the most insoluble of mysteries. Recently, however, some important light has been thrown on it. A brief outline of what is known is here given, as a fitting close of this little volume.

### 1. *The Invertebrate Eye.*

General sensibility to light is coextensive with life. It is found in the lowest protozoa and even in plants. This is not special sense; but, in accordance with a general law, all useful functions are by evolution soon specialized and localized in separate organs. It is probable that the first beginnings of the origin of a light-perceiving organ was determined by the stimulus of light itself on the epidermal surface. Certain groups of epithelial cells are thereby modified by elongation; a nerve fiber connects itself with each cell, and pigmentary matter is deposited at their base. This is the beginning of the light-perceiving part of the eye—viz., the *bacillary and pigmentary layers.* Such deposit of pigmentary matter for light-absorption and such specialization of nerve-terminals for light-perception, or response to ethereal vibration, may take place in any ex-

posed part of the body. Why it occurs in *spots* we know not, any more than we know why freckles come in spots. It may occur anywhere, but usually near the most important ganglion—the cephalic—and therefore in the head. Thus far we have a simple mechanism for perception of *light*, but not yet of *objects*, for we have not yet an *image-forming* instrument. Such a pigmented group of modified cells with specialized nerve

FIG. 148.

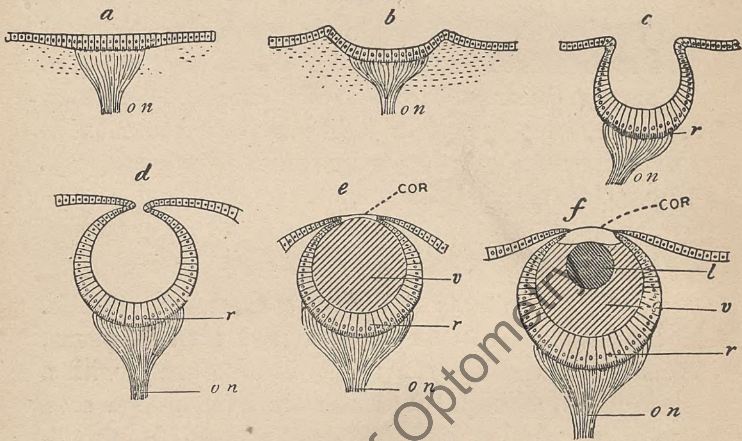



DIAGRAM REPRESENTING THE DIFFERENT STAGES IN THE EVOLUTION OF THE INVERTEBRATE EYE. *a b c*, eye-spots, no image; *d*, pin-hole image; *e*, simple lens-image; *f*, compound lens-image; *r*, retina; *o n*, optic nerve; *v*, vitreous humor; *l*, lens; *cor*, cornea.

attached is called an *eye-spot*. It is not yet an eye proper. Such eye-spots occur in very many lowest animals (Fig. 148, *a*).

The next step is a slight saucer-shaped depression of the modified spot with a slightly raised rim about it, as shown in *b*. This condition is found in the *solen*. In these headless mollusks the eye-spots are strung all along the edge of the mantle. Next the depression be-

comes deeper and cup-shaped, and the rim higher. This is found in the limpet (*Patella*), *c*. This is an improvement in so far as the light sensitive spot is protected and the impression is stronger by reverberation within the hollow. The eye-spot in these are on the *head*.

Thus far we have *eye-spots*, not true eyes—an organ perceiving *light* but not *objects*. The next step is found in the *nautilus* (*d*). In this case the raised margin of the hollow is drawn together until only a pin-hole-opening remains. Now for the first time we have an *inverted image* on the concave retina, but as yet only a *pin-hole-image*. We have already seen (page 19), the imperfection of such an image, and therefore the imperfect and blurred perception of objects.

The next step is found in the *trochus* and many other gasteropods—for example, the *snail* (*e*). The pin-hole-opening is closed although the point of closing remains transparent, and the hollow is filled with transparent refractive substance, which may be likened to the *vitreous* humor, although often called the lens. Here, then, we have a concave retina with bacillary layer—a refracting humor—a transparent cornea which may also be called a pupil. In this case we have an image formed by a lens—*a lens-image*—and therefore a far more perfect perception of objects.

The next and final step is found in the squid (*f*). In this animal that portion of the epithelial surface which covers the front of the eye, by a cuticular *ingrowth* forms a *lens;* and by folds of the epidermal surface lids are also formed. In fact, nearly all the parts of the vertebrate eye are found in these. In this case, therefore, we have, as in the vertebrate eye, not only a lens-image, but a *compound lens-image*.

That we have really given a true outline of the evo-

lution of the invertebrate eye is shown by the fact that these very steps are taken in the embryonic development of the eye of the squid. First a spot becomes depressed with a raised rim about it. Then the rim rises so as to make a deep hollow. Then the edges of the deep concave closes until only a pin-hole-opening is left. Then the opening closes and the hollow becomes a vesicle filled with refractive matter—the vitreous humor. Then a cuticular ingrowth from the central point of the surface forms the lens, and last iris and lids are added.

We have given only the barest outlines of the most important steps. There are many intermediate steps not mentioned. We have said nothing, also, of the compound eye of insects and crustaceans, because these are wholly peculiar and out of the line of the gradual evolution of this organ. Thus far we find nothing like an optic chiasm, nor fovea, and almost certainly the phenomena of binocular vision have not yet appeared. From the manner in which the fibers terminate it is evident that there can be no blind spot.

### 1. *The Vertebrate Eye.*

There are two great and essential differences in structure and mode of formation between the invertebrate and the vertebrate eye. 1. In the invertebrate eye the nerve fibers terminate directly in the *inner* ends of the nerve terminals or retinal rods, and the farther ends of these look *forward and outward* to receive the light. This seems the most natural mode, and is universal in the nerve terminals of all other senses in all animals. But in man and in all vertebrates the fibers of the optic nerve *turn back* on themselves and terminate in the *outer* ends of the rods and cones, and the

extreme ends of these latter look *backward and inward* (Fig. 24, page 53). This is wholly exceptional among nerve terminals. 2. It is seen that in invertebrates the *whole eye*—both retina and lens, both receiving plate and image-making instrument—is made from the epidermal epithelium. But in man and in all vertebrates embryology shows that the eye is formed partly by *in*folding of the epidermal epithelium and partly by the *out*folding of the brain vesicle and its epithelial lining; the image-making instrument is made from the epiderm, and the receptive plate, the retina, from the brain.

The steps of the whole process is briefly as follows: The brain in very early embryonic condition consists of three *hollow* vesicles in linear series. From the anterior one of these—the thalamus and cerebrum—originates the retinal part of the eye by an *out*folding on each side (Fig. 149, *A*). This outfolding continues until the subordinate vesicle—the optic vesicle, which is to become the retina—is connected with the brain vesicle only by a narrow neck which becomes the optic nerve (Fig. 149, *B*). In the meantime there has commenced a corresponding *in*folding from the epidermal surface to form the lens, and this is finally separated from its epidermal connection (*B*). Next, the optic vesicle is infolded on its anterior surface like a double nightcap, so that its middle part becomes widely separated from the lens (*C*). Of the two layers of the optic vesicle thus formed the anterior one, *r*, becomes the retina, and the posterior one, *ch*, the choroid. Now the whole interior of the brain vesicle, and therefore of the optic vesicle, is lined with a continuous pavement of epithelial cells. Therefore, in the two layers *r* and *ch* of the concave retina, the posterior surface of the anterior

layer, and the anterior surface of the posterior layer are epithelial (*D*). Now, as already said, the anterior layer becomes the retina, and therefore this posterior epithelial part becomes the bacillary layer. Similarly the anterior or epithelial part of the posterior layer becomes

Fig. 149.

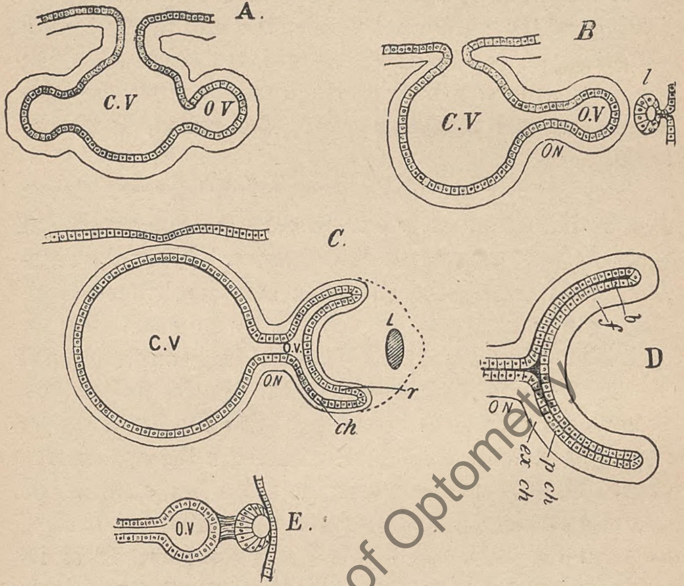



DIAGRAM REPRESENTING DIFFERENT STAGES IN THE DEVELOPMENT OF THE VERTEBRATE EYE. *C V*, cerebral vesicle; *O V*, optic vesicle; *r*, retina; *ch*, choroid; *b*, bacillary layer; *f*, fibrous layer; *l*, lens.

the pigmentary layer of the choroid. It is for this reason that the choroid is sometimes called a part of the retina. Like the retina, its origin is cerebral. From this mode of origin it is evident that the bacillary layer is the most posterior part of the retina, instead of the most anterior as in invertebrates: and that the fibres *turn back* to terminate in the rods and cones. It is

this peculiarity which makes a blind spot. The rest of the eye—the vitreous humor, the sclerotic, etc.—are formed by modification of the adjacent tissues.

It is seen, then, that in both the invertebrate and the vertebrate eye the retinal rods are transformed epithelial cells in which nerve fibers terminate; but in the one case these are of epidermal origin, in the other they originate from the epithelial lining of the brain. But the difference between these two modes of origin is not so great as it at first seems. For of the three original layers of the embryo—the ectoderm, the endoderm, and the mesoderm—the nerve centers are formed by an *infolding of the outer one—the ectoderm;* and therefore the lining epithelium of the brain vesicle and of the optic vesicle is really an *infolded part of the epidermal epithelium.* This is shown in Fig. 149, *A.*

### *Transition from Invertebrate to Vertebrate Eye.*

We see then that the line of evolution is continuous for the invertebrate eye, but how did the vertebrate eye come out of the invertebrate eye? There has been much discussion and many theories on this point, but the most probable one seems to be that of Beranek.* According to him the lens of the vertebrate eye *is not homologous with the lens of invertebrates, but rather with the whole eye of invertebrates.* The lens of the invertebrate eye is *not* formed by infolding of the epidermal surface, but by cuticular ingrowth at the point of closure of the optic vesicle. On the contrary, the lens of the *vertebrate* eye *is* formed by infolding of the epidermal surface, precisely as is the *whole* eye of invertebrates. Therefore, according to Beranek, in the primitive ver-

* Arch. des Sciences, vol. xxiv, p. 361, 1890.

tebrate, in fact before the vertebrate character was fully declared, the eye was formed after the manner of the invertebrate eye by epidermal infolding, but still in an imperfect condition, like *c* or *d* or *e*, Fig. 148, with the posterior part forming a retina, and fibers terminating in the usual way forward, but the optic vesicle (epidermo-optic vesicle) almost or quite *touching* the cephalic ganglion—i. e., with very short or no optic nerve (Fig. 149, *E*). Under these conditions direct stimulation of brain vesicle might well develop an additional optic vesicle (cerebro-optic vesicle) and an additional retina (cerebral retina). The new retina gradually replaced the old, the previous eye became the lens only, the retinal part being transformed into its posterior part, which is known to have a different structure from the anterior. The vitreous humor was of course afterward filled in between.

### *The perfecting of the Vertebrate Eye.*

The gradual evolution of the invertebrate eye is satisfactory. The transition from the invertebrate to the vertebrate eye is doubtful. But thenceforward the line of evolution is retaken and continues very regularly. We have already, in the previous chapter, some of these stages. We now give them briefly in the order of evolution.

In the lowest class of vertebrates—the *Fishes*—the eye, though formed on a different plan, is probably no better than a squid's. In fishes the eyes are placed well on the sides of the head, with their axes so widely divergent that their fields of view do not to any extent overlap. There is no consensual movement—each eye moves for itself. There is no common field of view—each eye looks for itself. There is no common point

of sight, and therefore no corresponding points of the two retinæ, and therefore also no binocular vision and no accurate judgment of solid form and relative distance based on binocular perspective.

Leaving out amphibians and reptiles, of which we know little, in *Birds*, although their optic axes are still widely divergent, yet by a unique arrangement of corresponding points about a very excentral fovea, binocular vision becomes possible for them, although their most perfect vision is still monocular. Birds are a very highly specialized class of vertebrates in many respects. It is not strange that they should be so in vision also.

In mammals the eyes are brought more and more to the front; the optic axes more and more nearly parallel in a passive state; the convergence of the axes on a point of sight becomes more and more easy; and with this comes the gradual development of corresponding points about a more highly organized *central area*, and thus all the phenomena of binocular vision and the judgments based thereon. But in mammals, generally, attentive observation and accurate perception of details at the point of sight is sacrificed to the greater advantages of an almost equal vision over a very wide field. The sight of mammals is no doubt keen, perhaps keener than ours in *detection* of objects, but not, I think, in determining their character.

Only in the anthropoid apes do we find the eyes brought fairly to the front with the optic axes parallel in a passive state, and a highly organized central fovea added, and vision thus made far more accurate at the point of sight. It is evident that this is the essential condition of attentive examination of the object looked at.

Finally, in man again, out of this there came *thoughtful* attention to the object looked at to the partial exclusion of other things, which seems to be a necessary condition of the emergence of the higher faculties of the mind. The existence of the fovea is necessary to the concentration of attention on the thing looked at. For how could we attend to one thing if all other things were equally distinctly seen? The same law is carried up from the physical into the higher psychical field. Concentration of thought on the subject thought of is a necessary condition of effective thought-work. The *mind's* eye, too, must have its fovea, or we do no effective work. The mind's eye also must be binocular (page 178) or we get no true moral perspective.

# INDEX.

THE END.

*THE BEGINNERS OF A NATION.* A History of the Source and Rise of the Earliest English Settlements in America, with Special Reference to the Life and Character of the People. The first volume in A History of Life in the United States. By EDWARD EGGLESTON. Small 8vo. Cloth, gilt top, uncut, with Maps, $1.50.

"Few works on the period which it covers can compare with this in point of mere literary attractiveness, and we fancy that many to whom its scholarly value will not appeal will read the volume with interest and delight."—*New York Evening Post.*

"Written with a firm grasp of the theme, inspired by ample knowledge, and made attractive by a vigorous and resonant style, the book will receive much attention. It is a great theme the author has taken up, and he grasps it with the confidence of a master."—*New York Times.*

"Mr. Eggleston's 'Beginners' is unique. No similar historical study has, to our knowledge, ever been done in the same way. Mr. Eggleston is a reliable reporter of facts; but he is also an exceedingly keen critic. He writes history without the effort to merge the critic in the historian. His sense of humor is never dormant. He renders some of the dullest passages in colonial annals actually amusing by his witty treatment of them. He finds a laugh for his readers where most of his predecessors have found yawns. And with all this he does not sacrifice the dignity of history for an instant."—*Boston Saturday Evening Gazette.*

"The delightful style, the clear flow of the narrative, the philosophical tone, and the able analysis of men and events will commend Mr. Eggleston's work to earnest students."—*Philadelphia Public Ledger.*

"The work is worthy of careful reading, not only because of the author's ability as a literary artist, but because of his conspicuous proficiency in interpreting the causes of and changes in American life and character."—*Boston Journal.*

"It is noticeable that Mr. Eggleston has followed no beaten track, but has drawn his own conclusions as to the early period, and they differ from the generally received version not a little. The book is stimulating and will prove of great value to the student of history."—*Minneapolis Journal.*

"A very interesting as well as a valuable book. . . . A distinct advance upon most that has been written, particularly of the settlement of New England."—*Newark Advertiser.*

"One of the most important books of the year. It is a work of art as well as of historical science, and its distinctive purpose is to give an insight into the real life and character of people. . . . The author's style is charming, and the history is fully as interesting as a novel."—*Brooklyn Standard-Union.*

"The value of Mr. Eggleston's work is in that it is really a history of 'life,' not merely a record of events. . . . The comprehensive purpose of his volume has been excellently performed. The book is eminently readable."—*Philadelphia Times.*

New York: D. APPLETON & CO., 72 Fifth Avenue.

*THE SUN.* By C. A. Young, Ph. D., LL. D., Professor of Astronomy in Princeton University. New and revised edition, with numerous Illustrations. 12mo. Cloth, $2.00.

"In this book we see a master's hand. Professor Young has no superiors, if he has rivals, among astronomers in this country. . . . 'The Sun' is a book of facts and achievements, and not a discussion of theories, and it will be read and appreciated by all scientific students, and not by them alone. Being written in untechnical language, it is equally adapted to a large class of educated readers not engaged in scientific pursuits."—*Journal of Education, Boston.*

"Professor Young's work is essentially a record of facts and achievements, rather than of theories and attempts at the interpretation of mysteries: yet the great questions still remaining to be answered are of course discussed, and in a masterly manner."—*Philadelphia Evening Bulletin.*

"It is one of the best books of popular science ever written, and deserves a host of readers."—*The Dial, Chicago.*

"You feel throughout that a master is leading you amid the intricacies and mazes of one of the most absorbing of studies. . . . Many a one whose views are hazy and dim will find here just that enlightenment, without an overburdened technicality, that will prove most useful."—*The Interior.*

*THE STORY OF THE SUN.* By Sir Robert S. Ball, F. R. S., author of "An Atlas of Astronomy," "The Cause of an Ice Age," etc. 8vo. Cloth, $5.00.

"Sir Robert Ball has the happy gift of making abstruse problems intelligible to the 'wayfaring man' by the aid of simple language and a few diagrams. Science moves so fast that there was room for a volume which should enlighten the general reader on the present state of knowledge about solar phenomena, and that place the present treatise admirably fills."—*London Chronicle.*

"As a specimen of the publisher's art it is superb. It is printed on paper which entices the reader to make marginal notes of reference to other books in his library, the type is large, the binding is excellent, and the volume is neither too large nor too small to handle without fatigue."—*New York Herald.*

*AN ATLAS OF ASTRONOMY.* By Sir Robert S. Ball, F. R. S., Professor of Astronomy and Geometry at the University of Cambridge; author of "Starland," "The Cause of an Ice Age," etc. With 72 Plates, Explanatory Text, and Complete Index. Small 4to. Cloth, $4.00.

"The high reputation of Sir Robert Ball as a writer on astronomy at once popular and scientific is in itself more than sufficient recommendation of his newly published 'Atlas of Astronomy.' The plates are clear and well arranged, and those of them which represent the more striking aspects of the more important heavenly bodies are very beautifully executed. The introduction is written with Sir Robert Ball's well-known lucidity and simplicity of exposition, and altogether the Atlas is admirably adapted to meet the needs and smooth the difficulties of young and inexperienced students of astronomy, as well as materially to assist the researches of those that are more advanced."—*London Times.*

New York: D. APPLETON & CO., 72 Fifth Avenue.

*HANDBOOK OF BIRDS OF EASTERN NORTH AMERICA.* With Keys to the Species, Descriptions of their Plumages, Nests, etc.; their Distribution and Migration. Treating of all the birds, some five hundred and forty in number, which have been found east of the Mississippi River, and from the Arctic Ocean to the Gulf of Mexico. By FRANK M. CHAPMAN, Assistant Curator of Mammalogy and Ornithology, American Museum of Natural History. With over 200 Illustrations. 12mo. Library Edition, cloth, $3.00; Pocket Edition, flexible covers, $3.50.

The author's position has not only given him exceptional opportunities for the preparation of a work which may be considered as authoritative, but has brought him in direct contact with beginners in the study of birds whose wants he thus thoroughly understands. The technicalities so confusing to the amateur are avoided, and by the use of illustrations, concise descriptions, analytical keys, dates of migration, and remarks on distribution, haunts, notes, and characteristic habits, the problem of identification, either in the field or study, is reduced to its simplest terms.

*OPINIONS OF ORNITHOLOGISTS AND THE PRESS.*

"Written in simple, non-technical language, with special reference to the needs of amateurs and bird-lovers, yet with an accuracy of detail that makes it a standard authority on the birds of eastern North America."—*J. A. Allen, Editor of The Auk.*

"I am delighted with the 'Handbook.' So entirely trustworthy and up to date that I can heartily recommend it. It seems to me the best all-around thing we have had yet."—*Olive Thorne Miller.*

"The 'Handbook' is destined to fill a place in ornithology similar to that held by Gray's 'Manual' in botany. One seldom finds so many good things in a single volume, and I can not recommend it too highly. Its conciseness and freedom from errors, together with its many original ideas, make it the standard work of its class."—*John H. Sage, Secretary of the American Ornithologists' Union.*

"Your charming and most useful little book. . . . I had good reason to expect an excellent book of the kind from your pen, and certainly have not been disappointed. We receive here very many inquiries concerning a popular book on birds, or rather, I should say, a book so combining popular and scientific features as to render it both entertaining and instructive. To all such inquiries I have been obliged to reply that no such book existed. Now, however, the 'long-felt want' has been satisfactorily supplied; and it will give me great pleasure to answer such inquiries in future in a different way."—*Robert Ridgway, United States National Museum, Washington, D. C.*

"A book so free from technicalities as to be intelligible to a fourteen-year-old boy, and so convenient and full of original information as to be indispensable to the working ornithologist. . . . As a handbook of the birds of eastern North America it is bound to supersede all other works."—*Science.*

"The author has succeeded in presenting to the reader clearly and vividly a vast amount of useful information."—*Philadelphia Press.*

"A valuable book, full of information compactly and conveniently arranged."—*New York Sun.*

"A charming book, of interest to every naturalist or student of natural history."—*Cincinnati Times-Star.*

"The book will meet a want felt by nearly every bird observer."—*Minneapolis Tribune.*

New York: D. APPLETON & CO., 72 Fifth Avenue.

*DEGENERATION.* By Professor MAX NORDAU. Translated from the second edition of the German work. 8vo. Cloth, $3.50.

"A powerful, trenchant, savage attack on all the leading literary and artistic idols of the time by a man of great intellectual power, immense range of knowledge, and the possessor of a lucid style rare among German writers, and becoming rarer everywhere, owing to the very influences which Nordau attacks with such unsparing energy, such eager hatred."—*London Chronicle.*

"The wit and learning, the literary skill and the scientific method, the righteous indignation, and the ungoverned prejudice displayed in Herr Max Nordau's treatise on 'Degeneration' attracted to it, on its first appearance in Germany, an attention that was partly admiring and partly astonished."—*London Standard.*

"Let us say at once that the English-reading public should be grateful for an English rendering of Max Nordau's polemic. It will provide society with a subject that may last as long as the present Government. . . . We read the pages without finding one dull, sometimes in reluctant agreement, sometimes with amused content, sometimes with angry indignation."—*London Saturday Review.*

"Herr Nordau's book fills a void, not merely in the systems of Lombroso, as he says, but in all existing systems of English and American criticism with which we are acquainted. It is not literary criticism, pure and simple, though it is not lacking in literary qualities of a high order, but it is something which has long been needed, for of literary criticism, so called, good, bad, and indifferent, there is always an abundance; but it is scientific criticism—the penetration to and the interpretation of the spirit within the letter, the apprehension of motives as well as means, and the comprehension of temporal effects as well as final results, its explanation, classification, and largely condemnation, for it is not a healthy condition which he has studied, but its absence, its loss; it is degeneration. . . . He has written a great book, which every thoughtful lover of art and literature and every serious student of sociology and morality should read carefully and ponder slowly and wisely."—*Richard Henry Stoddard, in The Mail and Express.*

"The book is one of more than ordinary interest. Nothing just like it has ever been written. Agree or disagree with its conclusions, wholly or in part, no one can fail to recognize the force of its argument and the timeliness of its injunctions."—*Chicago Evening Post.*

"A most absorbing book, and is likely to displace 'Trilby' as a subject of popular discussion."—*Chicago Tribune.*

"A ponderous volume whose every page is full of interest. So full is it in detail, so scientific in its method, so irresistible in its invitation to controversy, that it must get the worlds of arts and letters by the ears."—*New York Recorder.*

"The intense interest currently shown in the subject treated in the book, the original ideas it offers, and the imperturbable spirit of the scientific investigator which animates and sustains the author, will unquestionably command for it in this country the attention it has received abroad; and it may be safely predicted that 'Degeneration' already known here in literary circles, is destined to attain an immediate and widespread popularity."—*Philadelphia Telegraph.*

"This fascinating and most suggestive book gives a picture of the æsthetic manifestations of the times, drawn with rare adroitness, vigor, and command of satire, and it will be found to hold a place which has not been occupied."—*Cincinnati Commercial-Gazette.*

"Certain to arouse a storm of discussion."—*Philadelphia Ledger.*

"The interest which 'Degeneration' causes in the reader is intense."—*New York Times.*

New York: D. APPLETON & CO., 72 Fifth Avenue.

*THE STORY OF ARCHITECTURE. An Outline of the Styles in all Countries.* By CHARLES THOMPSON MATHEWS, Fellow of the American Institute of Architects; author of "The Renaissance under the Valois," etc. Illustrated. 12mo. Cloth, $3.00.

This compact yet comprehensive history of architecture offers a study of the effects of civilization upon architecture as a necessity and an art. Almost all the architectural monuments specially referred to are described from personal knowledge. American architecture receives careful attention, and Asiatic and Oriental architecture, usually neglected in such books, is discussed with an exceptional fullness of information. As regards the various phases of European architecture, the book will be found to be of constant value to travelers as well as to students, while in its comprehensiveness, informing quality, and the extent of the illustrations, it fills a place with the general reader which has long been vacant.

*SCHOOLS AND MASTERS OF SCULPTURE.* By A. G. RADCLIFFE. With 35 full-page Illustrations. 12mo. Cloth, $3.00.

"A comprehensive and judicious history of the art of sculpture, each chapter giving a clear and distinct account of the condition, character, and progress of the art. . . . Gives a very excellent account of the collections of sculpture in the American galleries and museums."—*Boston Transcript.*

"It would be difficult to name another work that would be so valuable to the general reader on the same subject as this book. . . . All has been set down that it is necessary for the lay reader to know."—*San Francisco Bulletin.*

"Free of all unnecessary technicalities, and abounds in the interesting facts the intelligent student of art will like to know and remember"—*Chicago Inter-Ocean.*

"Invaluable as a history of sculpture that can be understood by the general reader."—*Philadelphia Press.*

*SCHOOLS AND MASTERS OF PAINTING.* With an Appendix on the Principal Galleries of Europe. By A. G. RADCLIFFE. Illustrated. Entirely new edition, revised, and partly rewritten. 12mo. Cloth, $3.00; calf, $5.00.

"The volume is one of great practical utility, and may be used to advantage as an artistic guide-book by persons visiting the collections of Italy, France, and Germany for the first time. The twelve great pictures of the world, which are familiar by copies and engravings to all who have the slightest tincture of taste for art, are described in a special chapter, which affords a convenient stepping-stone to a just appreciation of the most celebrated masters of painting. An important feature of the work, and one which may save the traveler much time and expense, is the sketch presented in the appendix of the galleries of Florence, Rome, Paris, Venice, Dresden, and other European collections."—*New York Tribune.*

New York: D. APPLETON & CO., 72 Fifth Avenue.

*NEW EDITION OF PROF. HUXLEY'S ESSAYS.*

*COLLECTED ESSAYS.* By THOMAS H. HUXLEY. New complete edition, with revisions, the Essays being grouped according to general subject. In nine volumes, a new Introduction accompanying each volume. 12mo. Cloth, $1.25 per volume.

VOL. I.—METHOD AND RESULTS.
VOL. II.—DARWINIANA.
VOL. III.—SCIENCE AND EDUCATION.
VOL. IV.—SCIENCE AND HEBREW TRADITION.
VOL. V.—SCIENCE AND CHRISTIAN TRADITION.
VOL. VI.—HUME.
VOL. VII.—MAN'S PLACE IN NATURE.
VOL. VIII.—DISCOURSES, BIOLOGICAL AND GEOLOGICAL.
VOL. IX.—EVOLUTION AND ETHICS, AND OTHER ESSAYS.

"Mr. Huxley has covered a vast variety of topics during the last quarter of a century. It gives one an agreeable surprise to look over the tables of contents and note the immense territory which he has explored. To read these books carefully and studiously is to become thoroughly acquainted with the most advanced thought on a large number of topics."—*New York Herald.*

"The series will be a welcome one. There are few writings on the more abstruse problems of science better adapted to reading by the general public, and in this form the books will be well in the reach of the investigator. . . . The revisions are the last expected to be made by the author, and his introductions are none of earlier date than a few months ago [1893], so they may be considered his final and most authoritative utterances."—*Chicago Times.*

"It was inevitable that his essays should be called for in a completed form, and they will be a source of delight and profit to all who read them. He has always commanded a hearing, and as a master of the literary style in writing scientific essays he is worthy of a place among the great English essayists of the day. This edition of his essays will be widely read, and gives his scientific work a permanent form."—*Boston Herald.*

"A man whose brilliancy is so constant as that of Prof. Huxley will always command readers; and the utterances which are here collected are not the least in weight and luminous beauty of those with which the author has long delighted the reading world."—*Philadelphia Press.*

"The connected arrangement of the essays which their reissue permits brings into fuller relief Mr. Huxley's masterly powers of exposition. Sweeping the subject-matter clear of all logomachies, he lets the light of common day fall upon it. He shows that the place of hypothesis in science, as the starting point of verification of the phenomena to be explained, is but an extension of the assumptions which underlie actions in every-day affairs; and that the method of scientific investigation is only the method which rules the ordinary business of life."—*London Chronicle.*

New York: D. APPLETON & CO., 72 Fifth Avenue.

## THE ANTHROPOLOGICAL SERIES.

NOW READY.

*THE BEGINNINGS OF ART.* By ERNST GROSSE, Professor of Philosophy in the University of Freiburg. A new volume in the Anthropological Series, edited by Professor FREDERICK STARR. Illustrated. 12mo. Cloth, $1.75.

This is an inquiry into the laws which control the life and development of art, and into the relations existing between it and certain forms of civilization. The origin of an artistic activity should be sought among the most primitive peoples, like the native Australians, the Mincopies of the Andaman Islands, the Botocudos of South America, and the Eskimos; and with these alone the author studies his subject. Their arts are regarded as a social phenomenon and a social function, and are classified as arts of rest and arts of motion. The arts of rest comprise decoration, first of the body by scarification, painting, tattooing, and dress; and then of implements—painting and sculpture; while the arts of motion are the dance (a living sculpture), poetry or song, with rhythm, and music.

*WOMAN'S SHARE IN PRIMITIVE CULTURE.* By OTIS TUFTON MASON, A. M., Curator of the Department of Ethnology in the United States National Museum. With numerous Illustrations. 12mo. Cloth, $1.75.

"A most interesting *résumé* of the revelations which science has made concerning the habits of human beings in primitive times, and especially as to the place, the duties, and the customs of women."—*Philadelphia Inquirer.*

*THE PYGMIES.* By A. DE QUATREFAGES, late Professor of Anthropology at the Museum of Natural History, Paris. With numerous Illustrations. 12mo. Cloth, $1.75.

"Probably no one was better equipped to illustrate the general subject than Quatrefages. While constantly occupied upon the anatomical and osseous phases of his subject, he was none the less well acquainted with what literature and history had to say concerning the pygmies. . . . This book ought to be in every divinity school in which man as well as God is studied, and from which missionaries go out to convert the human being of reality and not the man of rhetoric and text-books."—*Boston Literary World.*

*THE BEGINNINGS OF WRITING.* By W. J. HOFFMAN, M. D. With numerous Illustrations. 12mo. Cloth, $1.75.

This interesting book gives a most attractive account of the rude methods employed by primitive man for recording his deeds. The earliest writing consists of pictographs which were traced on stone, wood, bone, skins, and various paperlike substances. Dr. Hoffman shows how the several classes of symbols used in these records are to be interpreted, and traces the growth of conventional signs up to syllabaries and alphabets—the two classes of signs employed by modern peoples.

IN PREPARATION.

*THE SOUTH SEA ISLANDERS.* By Dr. SCHMELTZ.
*THE ZUNI.* By FRANK HAMILTON CUSHING.
*THE AZTECS.* By Mrs. ZELIA NUTTALL.

D. APPLETON AND COMPANY, NEW YORK.

## PIONEERS OF SCIENCE IN AMERICA.

Sketches of their Lives and Scientific Work. Edited and revised by WILLIAM JAY YOUMANS, M. D. With Portraits. 8vo. Cloth, $4.00.

Impelled solely by an enthusiastic love of Nature, and neither asking nor receiving outside aid, these early workers opened the way and initiated the movement through which American science has reached its present commanding position. This book gives some account of these men, their early struggles, their scientific labors, and, whenever possible, something of their personal characteristics. This information, often very difficult to obtain, has been collected from a great variety of sources, with the utmost care to secure accuracy. It is presented in a series of sketches, some fifty in all, each with a single exception accompanied with a well-authenticated portrait.

"Fills a place that needed filling, and is likely to be widely read."—*N. Y. Sun.*

"It is certainly a useful and convenient volume, and readable too, if we judge correctly of the degree of accuracy of the whole by critical examination of those cases in which our own knowledge enables us to form an opinion. . . . In general, it seems to us that the handy volume is specially to be commended for setting in just historical perspective many of the earlier scientists who are neither very generally nor very well known."—*New York Evening Post.*

"A wonderfully interesting volume. Many a young man will find it fascinating. The compilation of the book is a work well done, well worth the doing."—*Philadelphia Press.*

"One of the most valuable books which we have received."—*Boston Advertiser.*

"A book of no little educational value. . . . An extremely valuable work of reference."—*Boston Beacon.*

"A valuable handbook for those whose work runs on these same lines, and is likely to prove of lasting interest to those for whom '*les documents humains*' are second only to history in importance—nay, are a vital part of history."—*Boston Transcript.*

"A biographical history of science in America, noteworthy for its completeness and scope. . . . All of the sketches are excellently prepared and unusually interesting."—*Chicago Record.*

"One of the most valuable contributions to American literature recently made. . . . The pleasing style in which these sketches are written, the plans taken to secure accuracy, and the information conveyed, combine to give them great value and interest. No better or more inspiring reading could be placed in the hands of an intelligent and aspiring young man."—*New York Christian Work.*

"A book whose interest and value are not for to-day or to-morrow, but for indefinite time."—*Rochester Herald.*

"It is difficult to imagine a reader of ordinary intelligence who would not be entertained by the book. . . . Conciseness, exactness, urbanity of tone, and interestingness are the four qualities which chiefly impress the reader of these sketches."—*Buffalo Express.*

"Full of interesting and valuable matter."—*The Churchman.*

New York: D. APPLETON & CO., 72 Fifth Avenue.

*THE STRUGGLE OF THE NATIONS:* Egypt, Syria, and Assyria. By Professor MASPERO. Edited by the Rev. Professor SAYCE. Translated by M. L. MCCLURE. With Map, 3 Colored Plates, and over 400 Illustrations. Uniform with "The Dawn of Civilization." Quarto. Cloth, $7.50.

This important work is a companion volume to "The Dawn of Civilization," and carries the history of the ancient peoples of the East from the twenty-fourth to the ninth century before our era. It embraces the sojourn of the Children of Israel in Egypt, and shows the historic connection between Egypt and Syria during the centuries immediately following the exodus. The book embodies the latest discoveries in the field of Egyptian and Oriental archæology, and there is no other work dealing so exhaustively with the period covered.

*THE DAWN OF CIVILIZATION.* (EGYPT AND CHALDÆA.) By Prof. G. MASPERO. Edited by Rev. Prof. A. H. SAYCE. Translated by M. L. MCCLURE. Revised and brought up to date by the Author. With Map and over 470 Illustrations. Quarto. Cloth, $7.50.

"The most sumptuous and elaborate work which has yet appeared on this theme. . . . The book should be in every well-equipped Oriental library, as the most complete work on the dawn of civilization. Its careful reading and studying will open a world of thought to any diligent student, and very largely broaden and enlarge his views of the grandeur, the stability, and the positive contributions of the civilization of that early day to the life and culture of our own times."—*Chicago Standard.*

"By all odds the best account of Egyptian and Assyrian theology, or, more properly speaking, theosophy, with which we are acquainted. . . . The book will arouse many enthusiasms. Its solid learning will enchant the scholar—its brilliancy will charm the general reader and tempt him into a region which he may have hesitated to enter."—*The Outlook.*

"The most complete reconstruction of that ancient life which has yet appeared in print. Maspero's great book will remain the standard work for a long time to come."—*London Daily News.*

*LIFE IN ANCIENT EGYPT AND ASSYRIA.* By G. MASPERO, late Director of Archæology in Egypt, and Member of the Institute of France. Translated by ALICE MORTON. With 188 Illustrations. 12mo. Cloth, $1.50.

"A lucid sketch, at once popular and learned, of daily life in Egypt at the time of Rameses II, and of Assyria in that of Assurbanipal. . . . As an Orientalist, M. Maspero stands in the front rank, and his learning is so well digested and so admirably subdued to the service of popular exposition, that it nowhere overwhelms and always interests the reader."—*London Times.*

"Only a writer who had distinguished himself as a student of Egyptian and Assyrian antiquities could have produced this work, which has none of the features of a modern book of travels in the East, but is an attempt to deal with ancient life as if one had been a contemporary with the people whose civilization and social usages are very largely restored."—*Boston Herald.*

New York: D. APPLETON & CO., 72 Fifth Avenue.

THE

INTERNATIONAL

SCIENTIFIC SERIES